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*Coastal Inlets Research Program*

# Morphologic Examination of the Stability of Pass Cavallo, Texas

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Pass Cavallo, TX, 5 April 2007

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**Abstract:** The study concerns the cross-sectional area stability of Pass Cavallo, a natural coastal inlet located in the southwest corner of Matagorda Bay, Texas. The width of Pass Cavallo has decreased since opening of the Matagorda Ship Channel (MSC) entrance to Matagorda Bay in 1966. The process of narrowing began after separation of Matagorda Bay into East Matagorda Bay and the present Matagorda Bay by formation of the Colorado River delta during 1929–1935. The deep-draft MSC enters the bay 3.5 miles (5.6 km) to the north of Pass Cavallo and is a more efficient tidal channel by joining with a deeper and more central portion of the bay.

Tidal inlets are maintained in a dynamic equilibrium through a balance of coastal and inlet processes. Conceptually, longshore transport of sediment by waves and the wave-induced current tends to fill an inlet, whereas the ebb-tide and flood-tide currents through the inlet scour its channel. The most reliable approach for examining inlet stability, and that taken here, is based upon accepted empirical predictive relations, supported by measurements made at Pass Cavallo. Collapse of a portion of the ebb-tidal shoal at Pass Cavallo after construction of the MSC entrance is posited as being responsible for much of the reduction in cross-sectional channel area of Pass Cavallo. Since the mid-1990s, the width of Pass Cavallo has been stable, suggesting the sediment load to the inlet from collapse of its ebb shoal has declined. Subject to the uncertainties that enter all coastal sediment processes studies, it is concluded that Pass Cavallo will remain open at its present dynamic cross-sectional channel area or undergo a moderate increase in channel area.

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# Preface

This report documents a study of the cross-sectional channel stability of Pass Cavallo, the natural permanent inlet to Matagorda Bay, TX. Pass Cavallo has experienced a reduction in cross-sectional area and width since the Matagorda Ship Channel deep-draft entrance was cut through Matagorda Peninsula to a more central and hydrodynamically efficient position in the bay. Both environmental and engineering concerns are associated with possible closure of Pass Cavallo. The major portion of this study was conducted for the U.S. Army Engineer District, Galveston (SWG), and Calhoun County [Texas] Navigation District to address these concerns.

This study was performed at the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) by Dr. Nicholas C. Kraus, Senior Scientists Group, and Dr. Brian K. Batten, formerly of CHL and presently at Dewberry & Davis, LLC. George E. Alcala was Project Manager for the SWG study. Assistance in previous related studies and the present study by Ronnie G. Barcak of SWG Operations Division is acknowledged. Dr. Lihwa Lin of the Coastal Engineering Branch, CHL, provided hydrodynamic information. Helpful discussions with members of the Calhoun County Navigation Board are also acknowledged. Work was performed under the general administrative supervision of Dr. William D. Martin, Deputy Director, CHL, and Thomas W. Richardson, Director, CHL.

Further geomorphic analysis, updates to the aerial photographic analysis since 2006, and report preparation were supported by the Coastal Inlets Research Program (CIRP), administered by Headquarters, U.S. Army Corps of Engineers (USACE). James E. Clausner, CHL, was the acting Technical Director for the Navigation Systems Program. Dr. Kraus is the CIRP Program Manager. The mission of the CIRP is to conduct applied research to improve the capability of the U.S. Army Corps of Engineers to manage federally maintained inlets, which are present on all coasts of the United States, covering the Atlantic Ocean, Gulf of Mexico, Pacific Ocean, Great Lakes, and U.S. territories. CIRP objectives are to advance knowledge and provide quantitative predictive tools to (a) make management of coastal inlet navigation projects, principally the design, maintenance, and

operation of channels and jetties, more effective to reduce the cost of dredging, and (b) preserve the adjacent beaches and estuary in a systems approach that treats the inlet, beach, and estuary as a unit. To achieve these objectives, the CIRP is organized in work units conducting research and development in hydrodynamic, sediment transport and morphology change modeling; navigation channels, adjacent beaches, and estuary; inlet structures and scour; laboratory and field investigations; and technology transfer.

COL Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

# 1 Introduction

The original motivation for this study was a request of the Calhoun County [Texas] Navigation District (CCND), implemented through contract with the U.S. Army Engineer District, Galveston (hereafter, Galveston District), to investigate the cross-sectional stability of Pass Cavallo, located in the southwest corner of Matagorda Bay, TX (Figure 1). The CCND has proposed widening and deepening of the Matagorda Ship Channel (MSC) from its present dimensions of 200 ft (61.0 m) bottom width and depth of 36 ft (11.0 m) mean low tide (mlt) to 400 ft (122.0 m) bottom width and 44 ft (13.4 m) depth for the bay segments of the channel. The datum mlt is a navigation datum defined by the Galveston District that lies below mean lower low water (Kraus et al. 1997) to account for the influence of strong wind and seasonal changes in water level along the Texas coastal and inland coastal waters. The Gulf segment is proposed to be enlarged from its present dimensions of 300 ft (91.4 m) by 38 ft (11.6 m) to 600 ft (182.9 m) by 46 ft (14.0 m). Considerable background on the waves,

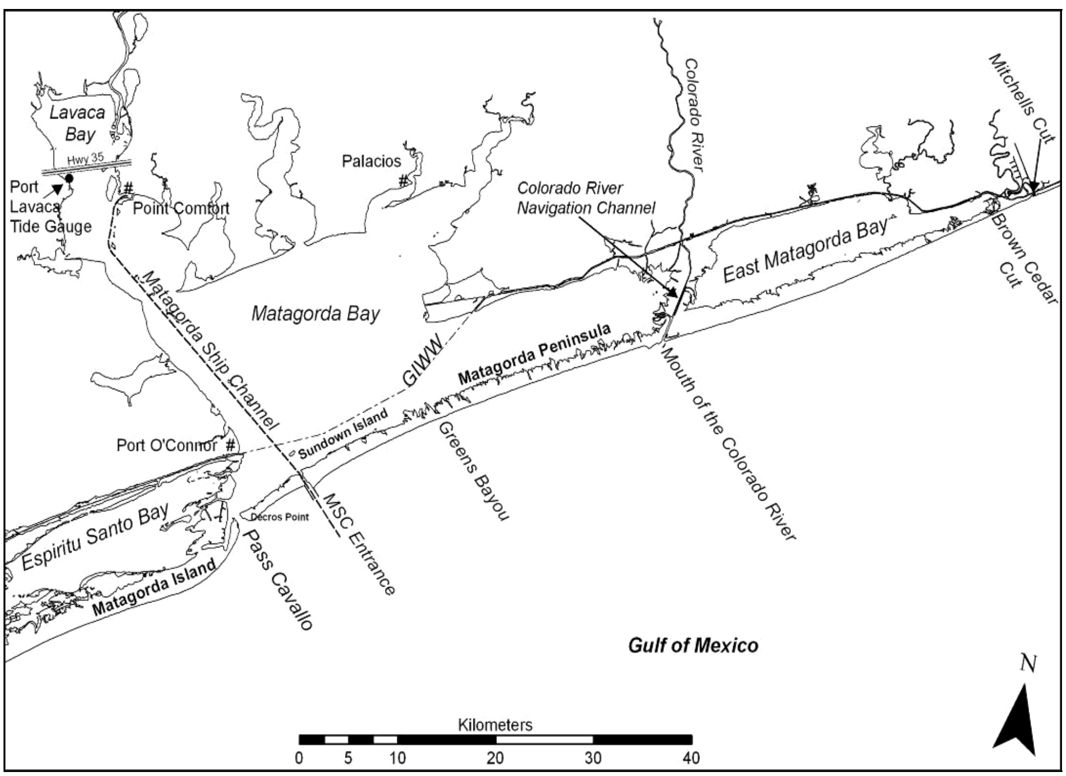


Figure 1. Detail map for Matagorda Bay and East Matagorda Bay.

current, wind, geomorphology, and history of engineering actions for the MSC is contained in Kraus et al. (2006b), prepared by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory, and is not reproduced here. Much of the content of this report is contained in a Memorandum for Record (Kraus et al. 2006a) submitted to the Galveston District and in a conference paper (Batten et al. 2007). The analysis was updated for the present report to examine width of Pass Cavallo observed in aerial photographs of April and September 2007. Geomorphic analysis of Pass Cavallo was extended, and references were also updated.

Pass Cavallo is the natural, permanent inlet to Matagorda Bay, and it has existed for at least 2,600 years, being in approximately the same location for the past 200 years (Harwood 1973). The volume of water (tidal prism) flowing through Pass Cavallo on ebb or flood tide has decreased in modern times. The first cause of this decrease was separation of the original Matagorda Bay into East Matagorda Bay and the present Matagorda Bay by growth of the Colorado River Delta across the bay from 1929 to 1935 (Wadsworth 1966; Bouma and Bryant 1969). The second and more dominant reason for decrease in the tidal prism at Pass Cavallo was cutting of the MSC entrance through Matagorda Peninsula in 1963, with completion of both jetties and dredging of the inner channel in 1966 (U.S. Army Corps of Engineers 1992).

Ward (1982) referred to Pass Cavallo as “shoal unstable,” and Van de Kreeke (1985) stated that Pass Cavallo would ultimately close because of the presence of the MSC entrance. Van de Kreeke (1990a, 1990b) concluded that multiple inlets to the same bay system cannot exist and that, eventually, at most one would remain. This conclusion was reached under the assumption of a constant basin surface area and uniformly fluctuating bay water level. In more recent work, Van de Kreeke and Borsje (2004) indicated that a more sophisticated analysis than done by Van de Kreeke (1990a, 1990b) can yield multiple stable inlets to one bay. Borsje (2003) examined the stability of the Pass Cavallo-MSC entrance with a linearized model of hydrodynamic equations for a dual-inlet system and concluded that only the MSC entrance would remain open. Wind tide was neglected from the analysis. Brouwer (2006) extended the analysis procedure in analytical work refining that of Van de Kreeke (199oa, 1990b) and Borsje (2003), noting that dual-inlet systems such as the Texel and Vlie basin in the western Dutch Wadden Sea indicate that a long-term equilibrium can be present. Stability analysis of a dual-inlet system and non-linear friction showed that, under certain conditions, a dual-inlet system can be stable.

Price (1952) noted that northerly wind fronts, common along the Texas coast from October through May, force water into the southwest corners of Texas bays, promoting existence and stability of inlets in those corners. The wind setup of water against the southwest shore of the bay produces an ebb discharge (wind tide) that adds to that of the astronomical tide. Price (1952) also found that Texas bays from Matagorda Bay to the south tend to have one inlet per bay, located in the southwest corner. Kraus (2007) examined the action of wind in a dual-inlet bay with a simple mathematical model and showed that the ebb current or the flood current can be enhanced or suppressed depending on the direction of wind and total friction of the respective inlets. Seabergh (2007) analyzed the stability of two inlets with jetties serving the same bay in Guatemala and concluded they were both near equilibrium and may be stable.

Therefore, there is uncertainty and concern that the existing MSC and possible enlargement of its entrance being considered by the CCND might cause or accelerate closure of Pass Cavallo. If Pass Cavallo were to close, the current at the MSC entrance would become stronger, promoting scour and potentially compromising navigation reliability. The natural water exchange and path through Pass Cavallo for organisms and nutrients would also be lost.

This study proceeded by conducting three activities: (a) a tidal inlet morphologic analysis based on accepted predictive equations, (b) field measurement of the entrance to Pass Cavallo, and (c) an update to 2007 of previous analyses of inlet width and spit growth. The analysis was supported by the literature review and hydrodynamic information calculated in the study of Kraus et al. (2006b), supplemented by additional calculations performed to investigate consequences to the tidal prism at Pass Cavallo if the MSC is deepened and widened. Recent aerial photographs since Kraus et al. (2006b) are compiled in Appendix A.

# 2 Critical Velocity Required to Maintain Stable Inlet

At Pass Cavallo, the tidal prism or the volume of water passing through an inlet on ebb or flood tide (discussed below) has been decreasing (Harwood 1973; Ward 1982). Figure 2 plots data compiled from those two sources as well as a point for year 2004, based on calculations with the model reported in Kraus et al. (2006b). Harwood (1973) studied the Pass Cavallo flood shoal and computed the tidal prism through estimation of effective bay surface area, including a portion of Espiritu Santo Bay, multiplied by the estimated tidal range. Ward (1982) determined tidal prisms based on measurements of the current and bathymetry in 1959 (prior to opening of the MSC) and in the 1970s. He found that, by the mid-1970s, the tidal prism at Pass Cavallo had decreased by half, similar to results of Harwood (1973).

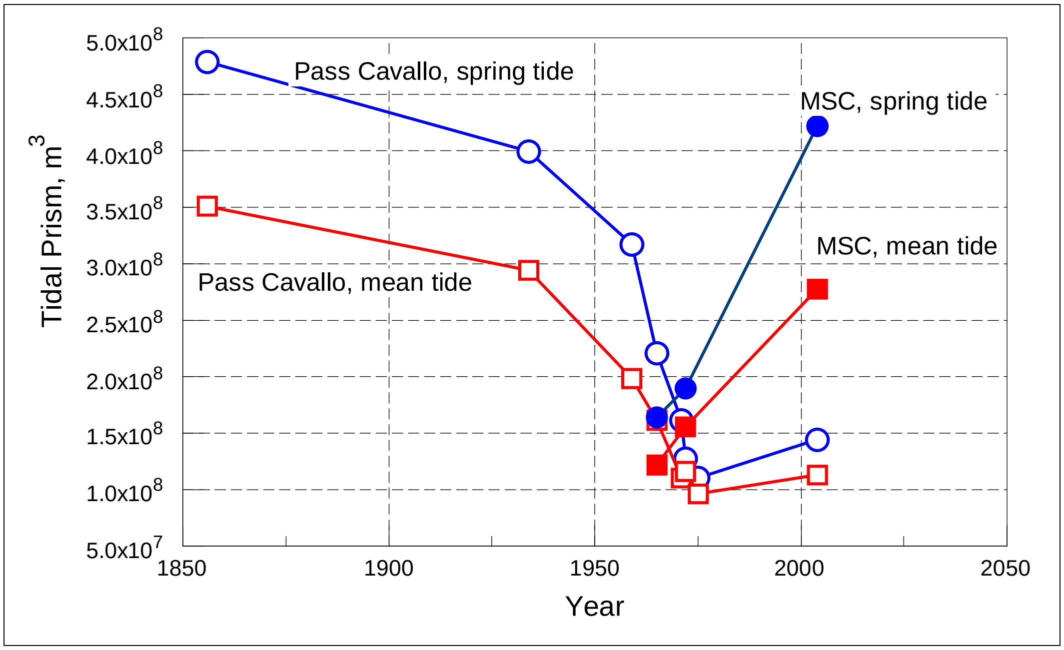


Figure 2. Estimated tidal prisms for Pass Cavallo and MSC. Lines indicate trends and are not to be interpreted as representing values.

In addition, Ward (1982) reports maximum values of the current "during the race of tide" through Pass Cavallo to be on order of 1 m/sec in 1959 and half that value in the 1970s. Ward (1982) notes that the tidal prisms for Pass Cavallo and the MSC in the 1970s were approximately the same, as can be seen in Figure 2. Our calculation for 2004, based on a calibrated two-dimensional flow model (Kraus et al. 2006b), indicates that the present tidal prism at the MSC is approximately three times that at Pass Cavallo. The tidal prisms for Pass Cavallo and the MSC are large and comparable to the larger Pacific coast inlets because the surface area of Texas bays is typically several times larger than the Pacific coast inlets, compensating for the relatively small tidal range as compared to the Pacific coast.

It is empirically known that a stable inlet located on a sandy coast will have a mean-maximum velocity through it of approximately 1 m/sec (Escoffier 1940; Bruun 1968). By "mean-maximum velocity" is meant the average of a regularly occurring maximum velocity, such as would be generated during spring tide. If it is assumed that the discharge is solely related to the tidal prism and that there is a sinusoidal tide with one component, the maximum discharge $D_m$ and tidal prism $P$ can be related as

$$P = \int_0^{T/2} D_m \sin\left(\frac{2\pi}{T}t\right)dt \tag{1}$$

where $T$ is the tidal period, and $t$ is time. The integration yields

$$D_m = \frac{\pi}{T}P \tag{2}$$

Tidal prism is defined as the volume of water exchanged between an estuary or lagoon and the open sea during one tidal period (between high to low tide in the bay, giving an ebb-tidal prism, or between low to high tide in the bay, giving a flood-tidal prism). Therefore, the integration limit in Equation 1 is taken to be $T/2$.

Tidal prism can also be calculated as the product of the effective bay surface area served by the subject inlet times the tidal range, or from a computation of water discharge, as through a numerical model. By definition of a discharge, the mean-maximum velocity $V_{mm}$ is

$$V_{mm} = \frac{D_m}{A_C} \tag{3}$$

in which $A_C$ is the minimum inlet channel cross-sectional area at mean sea level (msl).

Although refinements have been made in empirical predictive equations relating $A_C$ and $P$, it is convenient for present discussion to consider the linear relation found by O'Brien (1969), based in part on analysis of inlets without jetties, as follows:

$$A_C = C\,P \tag{4}$$

where $A_C$ is expressed in square meters, $P$ is expressed in cubic meters, and $C = 6.6 \times 10^{-5}$ with units $m^{-1}$. The original units of this equation in feet were converted to metric units for the present work.

Substitution of Equations 2 and 4 into Equation 3 gives (O'Brien 1969)

$$V_{mm} = \frac{\pi}{CT} \tag{5}$$

For a semidiurnal inlet, $T$ = 12 hr, 25 min = 44,712 sec. Then, Equation 5 yields $V_{mm}$ = 1.06 m/sec, in agreement with empirical observations, including those of Ward (1982) for Pass Cavallo in 1959. For a tide that is primarily diurnal, the tidal period is 89,424 sec, giving $V_{mm}$ = 0.53 m/sec. There are relatively few inlets worldwide in a diurnal tidal setting, making empirical validation of this result difficult.

The conclusion is that an inlet in a diurnal tidal setting may require a smaller mean-maximum tidal velocity to maintain channel cross-sectional area stability as compared to inlets in a semidiurnal setting, the more common type of inlet. For Pass Cavallo, this smaller value of $V_{mm}$ may be an underestimate, because the contribution to the ebb discharge by wind setup in the bay was neglected. A smaller value of $V_{mm}$ works in favor of the stability or preservation of Pass Cavallo.

# 3 Inlet Stability Examined with Empirical Relation and Measurement of Channel Cross-Sectional Area

This section compares a recent measurement of the channel cross-sectional area at Pass Cavallo to a standard empirical expression.

## Bathymetry survey of 23 May 2006

The survey was conducted by Frontier Surveying, Inc., Corpus Christi, TX, under contract with ERDC's Coastal and Hydraulics Laboratory, to determine the minimum cross-sectional area of Pass Cavallo. The survey was made with a Real-Time Kinematic (RTK) positioning system for which Global Positioning System signal corrections were transmitted from a reference receiver to the rover receiver on the survey boat. The vertical datum was North American Vertical Datum 1988 based on benchmark "Port O'Connor 1934 No. 1." These values were then converted to msl for the present analysis by reference to the tidal datums at Texas Coastal Ocean Observation Network tide station Port O'Connor, which is located close to Pass Cavallo (Figure 1). The horizontal datum was State Plane North Atlantic Datum 1983, Continuously Operating Reference Stations adjustment, Texas South Central Zone 4204. Estimated accuracy is ±0.30 m horizontal and ±0.15 m vertical.

Figure 3 shows the eight transects surveyed across the channel, together with the resultant bathymetry. The photograph serving as background is a geo-TIFF (Tagged Image File Format) referenced to a Digital Orthophoto Quarter Quadrangle (DOQQ) photograph of 1995, accurate to approximately ±1 m. The location of the RTK survey location closely matches the photograph. At the time of the survey, the channel was close to Matagorda Peninsula and oriented almost east-west. Considerable sand can be observed in the ebb shoal segment to the south.

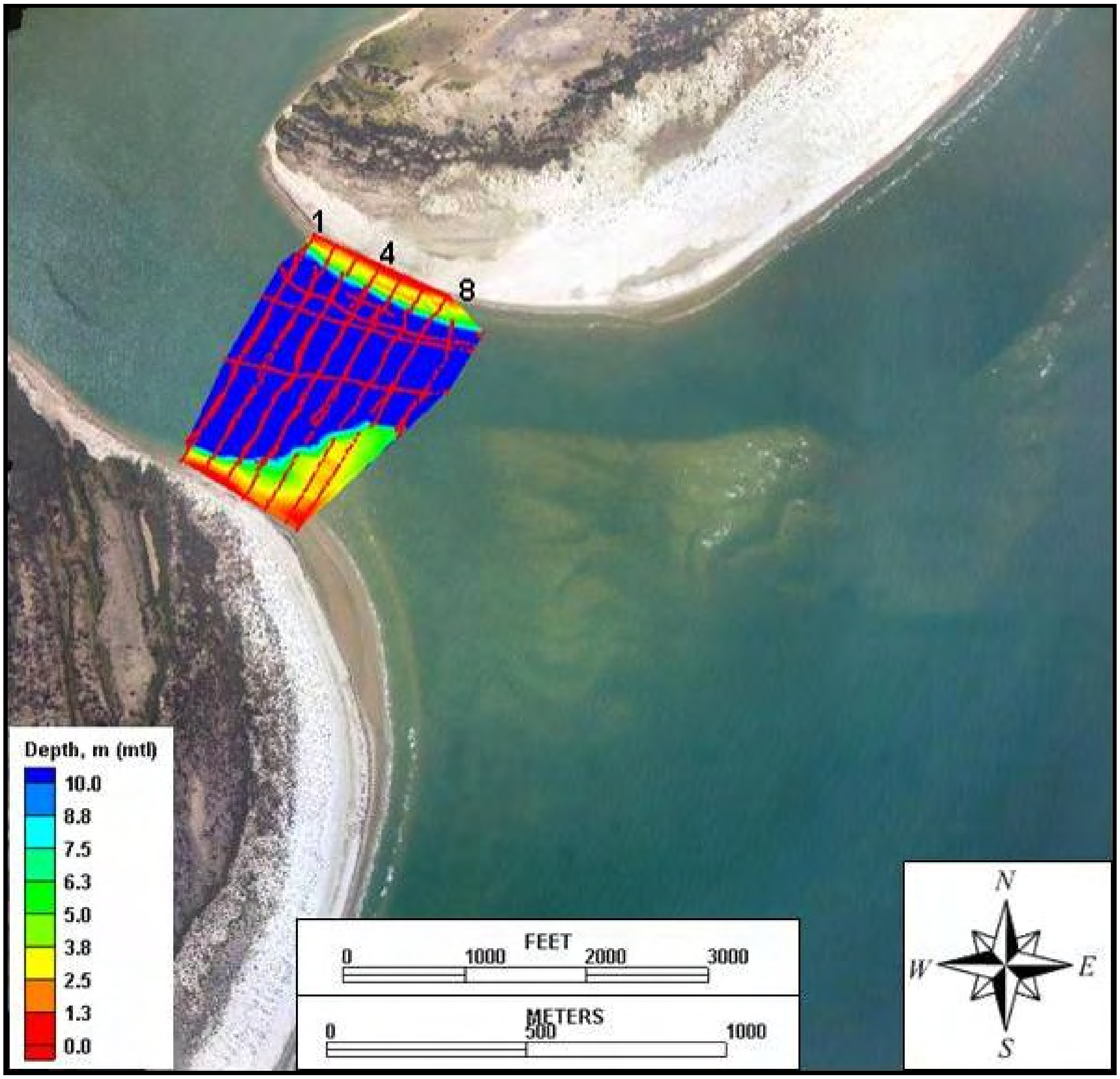


Figure 3. Pass Cavallo cross-sectional survey area of 23 May 2006, superimposed on photograph of 16 May 2006 (photograph by Lanmon Aerial Photography, Inc., Corpus Christi, TX).

Depth across the eight transects is shown in Figure 4. The maximum depth in the channel reaches 9 m msl, and the cross-sectional area, calculated by integrating the curves to msl, ranged from about 3,470 $m^2$ along Transect 1 to a minimum of 2,060 $m^2$ along Transect 8. The latter transect was the limit of being able to navigate the survey boat abeam to incident waves in the Gulf of Mexico that day. Transects 5-8 were interrupted to the south by a large shoal that appears to be approaching the channel from Matagorda Island.

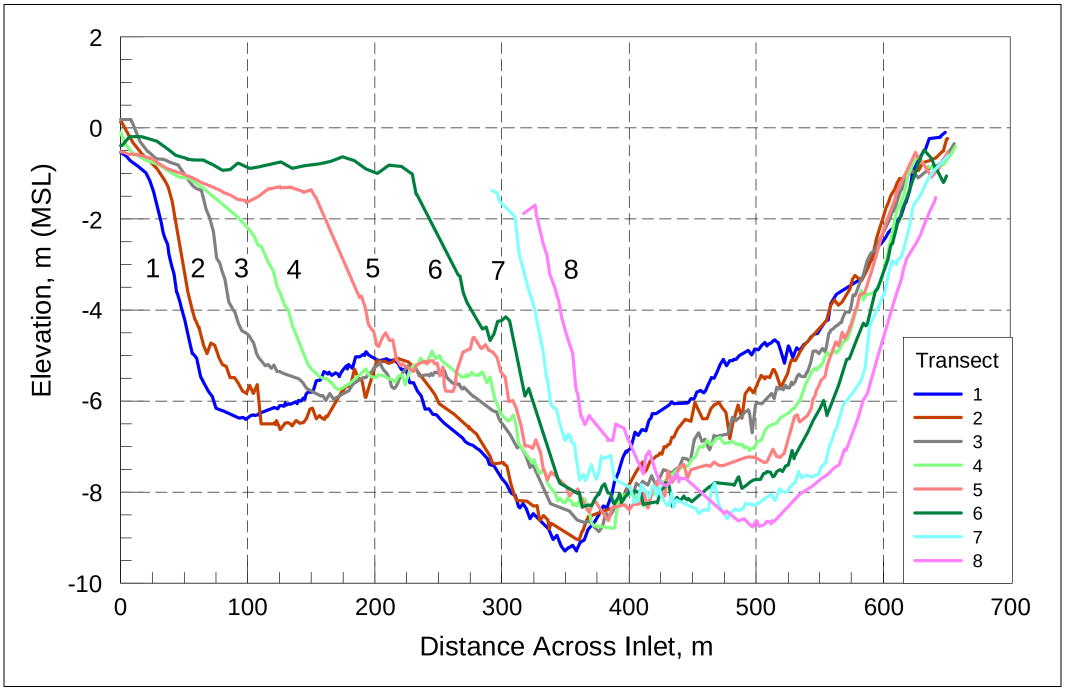


Figure 4. Surveys along eight transects in Pass Cavallo, 23 May 2006. Transect locations are numbered from 1 to 8, starting in Matagorda Bay in Figure 3.

## Empirical estimation of channel cross-sectional area based on tidal prism

Empirical relations are available that relate minimum inlet channel cross-sectional area below msl for a stable inlet and tidal prism, and such considerations have recently been shown to hold world-wide. Figure 5 is a plot of data compiled from six countries, consistent with the relation $A_C = 1.75 \times 10^{-04} P^{0.952}$ ($A_C$ in m$^2$, $P$ in m$^3$), which may be considered a global relation that can be applied if no data are available for a given inlet.

Jarrett (1976) analyzed 108 inlets (yielding 162 data points) along the Atlantic Ocean, Gulf of Mexico, and Pacific Ocean coasts of the United States. His objectives were to determine if inlets on the three coasts follow the same inlet cross-sectional area–tidal prism relation, and if inlet stabilization altered that relation. With relatively high correlation coefficients, all predictive relations were found to fit the form

$$A_C = CP^n \tag{6}$$

in which $C$ and $n$ are empirically determined. Jarrett (1976) found the exponent $n$ to vary between 0.86 and 1.10 for inlets with no jetty or with a single jetty and between 0.85 and 0.95 for inlets with two jetties.

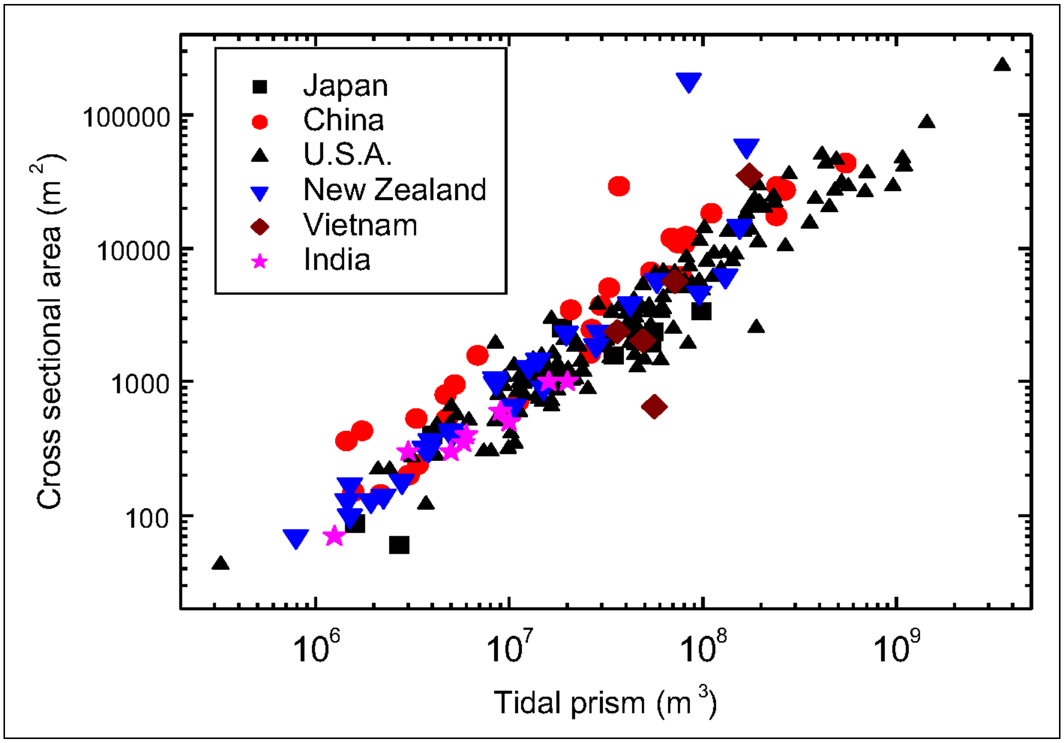


Figure 5. Global tidal inlet cross-sectional area vs. tidal prism relation.

Byrne et al. (1980), Riedel and Gourlay (1980), and Hume and Herdendorf (1990) studied inlet channel stability on coasts sheltered from direct wave incidence and demonstrated that larger values of the empirical coefficient $C$ and smaller values of $n$ apply to coasts with limited littoral transport. Quoting Riedel and Gourlay (1980), "In contrast (to exposed coasts), for sheltered inlets the littoral drift rate is small and, consequently, a much smaller volume of material needs to be moved out of the entrance in each tidal cycle." The aforementioned three studies also indicate that the mean-maximum velocity required to maintain stability of the inlet channel is less (reaching approximately one-third less) than the typical 1 m/sec required to maintain an inlet channel on an exposed coast for a semidiurnal tide.

For analysis of the stability of Pass Cavallo, the Jarrett (1976) relation describing unjettied and single inlets for the Gulf Coast, developed from 30 data points, was selected as most appropriate. This relation is $A_C = 6.992 \times 10^{-04} P^{0.86}$ (metric units). With the 2004 value of tidal prism ($1.44 \times 108$ m$^3$) from Figure 2, the result is $A_C = 7{,}300$ m$^2$. This predicted value of $A_C$ is about two to three times larger than the values measured along Transect 1 and Transect 8, respectively. This result indicates that Pass Cavallo is presently experiencing a surplus of sediment, and the probable source is identified in the next chapter.

# 4 Ebb-Tidal Shoal Abandonment and New Equilibrium at Pass Cavallo

Ebb-tidal shoals or simply ebb shoals (called “ebb deltas” by geologists) form as a balance between the scouring capacity of the ebb current at an inlet and the capacity of waves to transport material to and away from the inlet. Harwood (1973) studied the flood shoal at Pass Cavallo, which is an extensive sandy platform that protrudes into Espiritu Santo Bay. Flood shoals do not directly depend on wave action for their formation and consist of sediment that enters the channel that is transported toward the bay by the flood-tidal current. Ebb shoals and flood shoals greatly differ in that, if the inlet reduces in size, migrates, or closes, the ebb shoal will be acted upon by waves and will partially or completely disperse, whereas the flood shoal will remain in place and intact.

An entire ebb shoal or just a portion of it can become abandoned if an inlet is relocated, if jetties are constructed to confine the ebb current, of if the tidal prism, hence ebb current, decreases. Pope (1991) documents inlets on the southeast coast of the United States for which jetty construction restricted the width of the ebb jet and caused abandonment of lateral portions of the ebb shoal, which then migrated on shore. Kraus (2006) gives a more general discussion of ebb-shoal abandonment and cites other reference sources. The abandoned portions of ebb shoals will migrate onshore, called “ebb-shoal collapse,” if those portions are located within the littoral zone.

Volumes of ebb shoals can be large and reach hundreds of millions of cubic meters for large inlets, meaning those with large tidal prisms. Harwood (1973) contains reproductions of the old coastal surveys depicting an island called “Pelican Island” as part of the historic ebb shoal at Pass Cavallo. The inlet was so large and natural channels through it so variable that a navigation channel could not be maintained economically (U.S. Army Corps of Engineers 1992), one reason for creation of the MSC.

Ebb shoal volume was found to be well correlated with tidal prism by Walton and Adams (1976), who also concluded that ebb shoal volumes can be larger on coasts receiving less wave exposure, because there would be less transporting capacity to remove the sediment deposited by the ebb current. The following empirical formula was presented by Walton and Adams (1976) to compute the ebb shoal volume $V_E$ for inlets in equilibrium on mildly exposed (to waves) coasts. The Galveston Entrance, TX, and Aransas Pass, TX, which are on the same coast as Pass Cavallo, were among the 16 inlets analyzed:

$$V_E = 8.458 \times 10^{-3} P^{1.23} \tag{7}$$

in which $V_E$ and $P$ are expressed in cubic meters, a conversion from units of cubic yards and cubic feet, respectively, from the original formula.

For year 1856, Harwood (1973) estimated the tidal prism of Pass Cavallo to be $4.79 \times 10^8$ m$^3$, and for year 2004, we estimate it at $1.84 \times 10^8$ m$^3$ (Table 1). These tidal prisms give $V_E$-values of about 400 million m$^3$ and 124 million m$^3$, respectively, assuming the ebb shoal achieved equilibrium volume for each of the tidal prisms. If these estimates are approximately correct, they indicate that since about 1966, when the MSC was cut, the excess volume (400 – 124 = 276 million m$^3$) has been abandoned by the gradually declining tidal prism at Pass Cavallo. Most of the abandoned sand-sized material in the ebb shoal will migrate down-coast and onto the shore (the ebb shoal collapse). This material will be partially responsible for growth and volume increase of the spits to either side of the inlet.

Table 1. Tidal prism (millions of cubic meters).

| Year or Action | Pass Cavallo | | MSC | |
|---|---|---|---|---|
| | Spring Tide | Mean Tide | Spring Tide | Mean Tide |
| 1856 | 478.6 | 351.1 | Not open | Not open |
| 1934 | 399.3 | 294.5 | Not open | Not open |
| 1959 | 317.1 | 198.2 | Not open | Not open |
| 1965 | 220.9 | 161.4 | 164.2 | 118.9 |
| 1971 | 163.7 | 110.4 | Not available | Not available |
| 1972 | 127.4 | 116.1 | 189.7 | 155.7 |
| 1975 | 110.4 | 96.3 | Not available | Not Available |
| 2004 | 184.1 | 113.3 | 478.6 | 305.8 |
| Alt 3[a] | 164.2 | 110.4 | 515.4 | 359.6 |
| Deepened and Widened Project (Recalculated with Revised 2004 Model Bathymetry) | | | | |
| 2004 | 175.6 | 110.4 | 461.6 | 290.2 |
| Deepen, widen | 175.6 | 110.4 | 470.1 | 294.5 |
| Deepen, widen, remove south bottleneck | 172.7 | 110.4 | 455.9 | 286.0 |
| Deepen, widen, remove north and south bottlenecks | 167.1 | 107.6 | 495.5 | 303.0 |

[a] See Kraus et al. (2006b) for discussion of alternatives. Alt 3 refers to removal of both bottleneck revetments in the MSC entrance.

The hypothesis for abandonment and collapse of a portion of the ebb shoal at Pass Cavallo is qualitatively supported by the analysis of Morton (1977), who noted that spit progradation and shoreline advance at Decros Point (western end of Matagorda Peninsula) did not appear to be compatible with recession of the shoreline downdrift of the MSC. Morton (1977) found excess material in the downdrift compartment, described the source as problematic, and suggested bank and channel erosion as potential sources. These sources are considered by the authors of the present report to be inadequate to account for the observed long-term spit growth. It is hypothesized here that sediment from offshore deposits is also contributing to growth at the end of Matagorda Peninsula. The likely source is partial abandonment and collapse of the ebb shoal at Pass Cavallo. Because the tidal prism has been reduced since formation of the Colorado River delta in 1935 and completion of the MSC jetties in 1966, much of the existing ebb shoal would gradually migrate onshore, as estimated in the preceding paragraph.

Matagorda Island probably owes its origin to ancient sand deposits from a previous low stand in sea level, whereas Matagorda Peninsula is a relatively young feature in comparison, owing its origin to sand supplied from the Brazos River and old Colorado River when it opened to the Gulf of Mexico (Wilkinson 1974). Pass Cavallo gradually migrated south, in the direction of net longshore sand transport, with growth of Matagorda Peninsula. Pass Cavallo reached its present location and was likely stopped by the presence of Matagorda Island, some 200 years ago (Harwood 1973). Pass Cavallo exhibits characteristics of what are called tide-dominated inlets, possessing a deep ebb channel lined by margin linear bars (Hayes 1979; Hubbard et al. 1979). Such morphology is indicative of a strong tidal current that can overcome transport by waves. The bulge at the end of Matagorda Peninsula may have formed in part from collapse of the ebb shoal and as the start of a sand bridge for material transported south that will bypass Pass Cavallo. The large drumstick shape of the northern end of Matagorda Island is attributed to wave refraction on the ebb shoal, reversing wave direction from the dominant southward direction (Hayes et al. 1970).

Spit progradation on the west side of Pass Cavallo requires examination, because this spit growth is partially responsible for inlet constriction. Along Matagorda Peninsula, it is clear from shoreline response at the MSC jetties that the predominant direction of littoral drift is from the northeast to the southwest. Temporary reversals in transport occur during southerly winds and during some storms (Paine and Morton 1989). Under these conditions and owing to wave refraction over the ebb shoal (Hayes et al. 1970), a spit emerged from Matagorda Island and prograded 3.5 km northeast into the inlet, also requiring a considerable amount of material. The southwest tip of the Matagorda Island shoreline experienced recession through this period (Paine and Morton 1989). It is likely that material sourced from this erosion contributed to support growth of the spit during that time.

It is hypothesized here that sediment from offshore deposits also contributes to growth at the end of Matagorda Peninsula and Matagorda Island. The likely source is partial abandonment and collapse of the ebb shoal at Pass Cavallo. This theory is also supported by the limited bathymetric data available for the inlet (modern data are not available for comparison). Figure 6 shows a 1934 National Ocean Service (NOS) hydrographic survey (NOS 1934) of Pass Cavallo, overlaid with the 1995 Texas shoreline (Bureau of Economic Geology 2004). An oblique aerial photograph of Pass Cavallo is shown as Figure 7 for further visualization. At the time of the survey, the inlet channel was located at the western side of the inlet, and a large ebb shoal is apparent offshore of the terminus of Matagorda Island. Shoreline recession along the eastern extent of Matagorda Island, in addition to the volume of material contained within this shoal, support the deposit as being a main source of material for spit progradation into the inlet complex.

Most of the abandonment has occurred gradually over the 43 years since opening of the MSC. After the material in the abandoned shoal is depleted, a significant source of sand tending to close Pass Cavallo will be gone, and it is feasible that the inlet will grow (but not back to its historic maximum because of the reduction in tidal prism). The trend in Pass Cavallo for a new equilibrium or possible growth is consistent with the shoreline change analysis of inlet width, described in the next chapter.

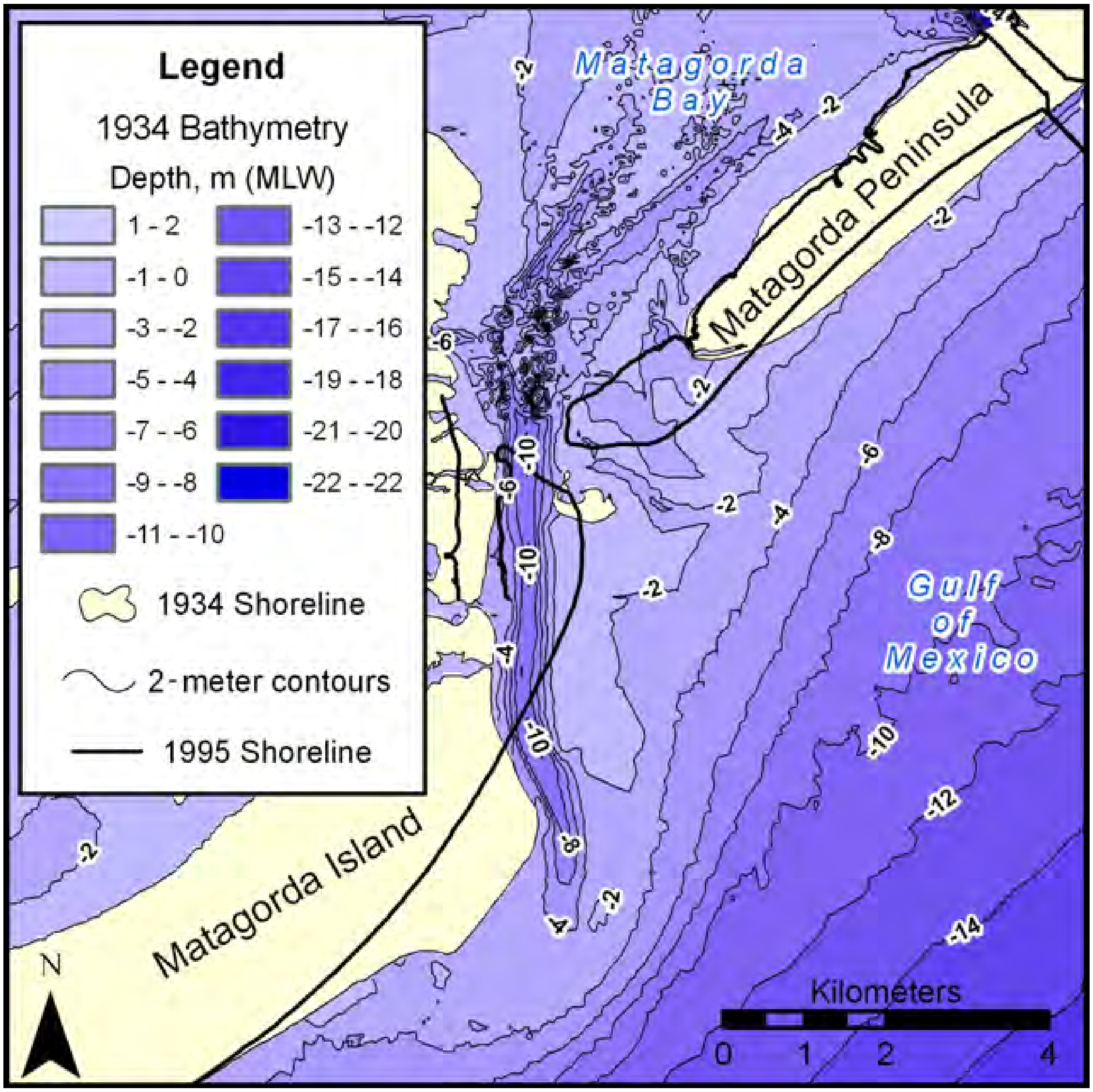


Figure 6. Pass Cavallo channel and ebb shoal in 1934.

Table 1 compiles historic data for tidal prism (as plotted in Figure 2) together with recently performed numerical calculations of tidal prism made with the same calibrated hydrodynamic model described by Kraus et al. (2006b). The recent calculations include deepening and widening of the MSC navigation channel, together with removal of one or both of the bottleneck revetments in the entrance. The deepening and widening only slightly increase the tidal prism that passes through the MSC and slightly decrease the tidal prism through Pass Cavallo. The changes in tidal prism are small because the channel occupies a relatively small amount of the cross section of the MSC entrance. Therefore, the deepening and widening of the MSC as proposed by the CCND will not significantly alter the trend of stability of Pass Cavallo.

Figure 7. Oblique aerial view of Pass Cavallo, 16 August 2006 (photograph reproduced with permission of Dr. Richard L. Watson, http://texascoastgeology.com/passes/passcavallo.html).

# 5 Update on Observed Width of Pass Cavallo, Spit Length, and Shoreline Change

This chapter updates a prior morphologic analysis of shoreline change conducted for Pass Cavallo by Kraus et al. (2006b) with interpretation of aerial photographs taken on 28 February 2006, 16 May 2006, 5 April 2007, and 10 September 2007.

Pass Cavallo was historically stable until the 20th century, as discussed by Harwood (1973). Opening of the MSC across Matagorda Peninsula in 1966 and subsequent capture of the majority of the Matagorda Bay tidal prism have resulted in shoaling and narrowing of Pass Cavallo. The width of Pass Cavallo reached a minimum in the 1990s, as Matagorda Peninsula prograded southwest and Matagorda Island prograded northeast into the inlet. Following this minimum width in 1995 to 2003, the inlet entered a period of apparent dynamic equilibrium with the present hydraulic forcing, and it has slightly widened. For the present analysis, morphologic change at Pass Cavallo was generalized into three eras: Era I for a time of relative stability prior to 1963, Era II for a time of instability and rapid narrowing from 1963 to the late 1980s, and Era III for a time of relative stability subsequent to 1990. These findings are discussed next.

## Geomorphic analysis updated with 28 February 2006, 16 May 2006, 5 April 2007, and 10 September 2007 aerial photographs

The following section describes methodology employed in the analysis of shoreline evolution and changes in inlet width at Pass Cavallo.

### Aerial photography

Four sets of aerial photographs were ordered for this updated study (compiled in Appendix A) and acquired on 28 February 2006, 16 May 2006, 5 April 2007, and 10 September 2007 by Lanmon Aerial Photography, Inc., under contract with the ERDC. They were provided for analysis in geo-tiff format. The 28 February images were 0.5-m resolution, and image quality was excellent. Waves during the time of the image capture were energetic, with breaking waves observed in a wide surf-zone.

For 16 May 2006, two images were available for Pass Cavallo (approximately 1,000 and 2,000 ft altitude, 0.5- and 0.8-m resolution, respectively), and a single image for the MSC (2,000 ft altitude, 0.8-m resolution). For these data, the high-altitude (larger scale) image had poor contrast, and shoreline position was difficult to identify (Figure 8); thus, the shoreline was limited to the extent of the low-altitude image. The 5 April and 10 September 2007 images were at the same altitudes (resolution improved to 0.3 and 0.5 m) and available for Pass Cavallo only. Image quality for both dates was satisfactory. Waves at the time of the April photography were energetic, whereas those during the September photograph appear more typical for the site.

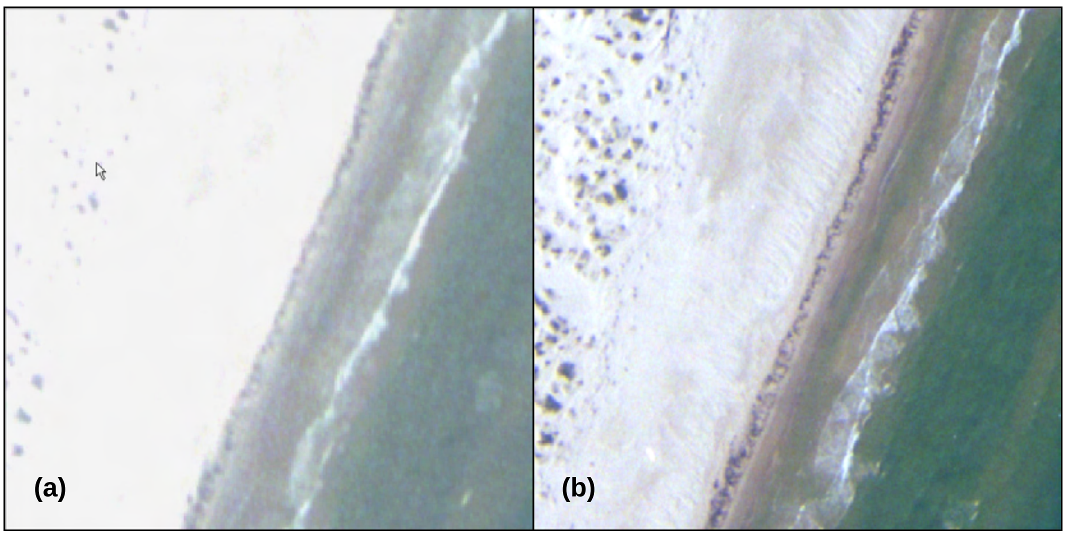


Figure 8. Example of image quality with (a) larger scale image, and (b) smaller scale image.

## Image rectification

Images were delivered georeferenced to the Universal Transverse Mercator Zone 14 North coordinate system. The methodology and accuracy of the geo-referencing was unknown; therefore, photographs were re-rectified to 1995 1-m DOQQ available from the Texas Natural Resources Information System (TNRIS 1995). This photoset provided a high-accuracy (National Map Accuracy Standards; see Anders and Byrnes 1991), high-resolution (1-m) base for rectification. The study area has few stable well-defined control points available for image rectification. Given this limitation, control points were improvised from geomorphologic features (such as ground depressions) and vegetation. Image rectification was performed within the Environmental Systems Research Institute ArcGIS 9.0 and consisted of 7 to 10 control points for each image. Because of the relative lack of control and distribution of control points, the majority of the imagery was rectified using a first-order polynomial transformation. Rectification accuracy was evaluated qualitatively by the goodness-of-fit of the output image to the TNRIS DOQQs.

### Shoreline definition

Consistent with the previous analysis, the shoreline definition here is the high water line (hwl). The hwl is defined as “the intersection of land with the water surface at an elevation of high water,” which can be interpreted by a continuous line of deposition of debris on the foreshore (National Oceanographic and Atmospheric Administration 2000). The hwl is an interpreted shoreline, as opposed to the mean high water line, which is determined through the measurement and analysis of water levels at a site (Kraus and Rosati 1997). The hwl is the most commonly used shoreline indicator in the United States because of ease of interpretation in the field and on aerial photography (Leatherman 2003).

The hwl is interpreted from aerial photographs by noting the position of a color-saturation change on the sub-aerial beach. This interpretation is not to be confused with the water-saturated zone, which occurs close to the water line (Leatherman 2003). This definition becomes problematic if interpreting aerial photographs that are of poor quality, either under- or overexposed, resulting in a washing out of the sub-aerial beach. Specialized experience and manipulation of the digital image are employed to identify these features and create an accurate representation of the shoreline. Modern aerial photography and orthophotographs are of much higher resolution and allow distinction of the hwl with less manipulation of the digital data.

### Shoreline digitization procedure

If not readily apparent, the position of the hwl was enhanced through standard deviation and image histogram stretching techniques prior to digitizing. Viewer scale was set according to image resolution to maximize accuracy of the digitized line. Image scale was held constant as the shoreline was digitized across each image or series of images. Digitizing began at the west end of Matagorda Peninsula and ended at the east end for the Gulf of Mexico shoreline. Point density was varied as necessary to capture alongshore variations in shoreline position. Once the shoreline was complete, the digitized line was reviewed and individual points or sections adjusted as needed.

## Shoreline and spit length analysis

Shoreline position was measured against a baseline established parallel to the local shoreline orientation at an interval of 15.2 m by means of the ArcView 3.2 extension *BeachTools* (Hoeke et al. 2001) (Figure 9). Shoreline positions relative to the baseline were exported from the GIS, and change rates were then calculated in Matlab®. A low-pass filter was applied to the change rates to remove high-frequency noise induced by the dense spatial sampling of the shorelines.


Figure 9. Reference baseline for shoreline change analysis along Matagorda Peninsula.

Spit length was evaluated by establishing two baselines fronting the Gulf of Mexico shorelines of Matagorda Peninsula and Matagorda Island (Figure 10). For Matagorda Peninsula, the baseline originated at the south jetty of the MSC. The origin of the Matagorda Island baseline was placed at the observed origin of the Matagorda Island spit. Spit length along each baseline was measured to the maximum extent of each spit from the origin using *BeachTools* with transects spaced at 3-m intervals.

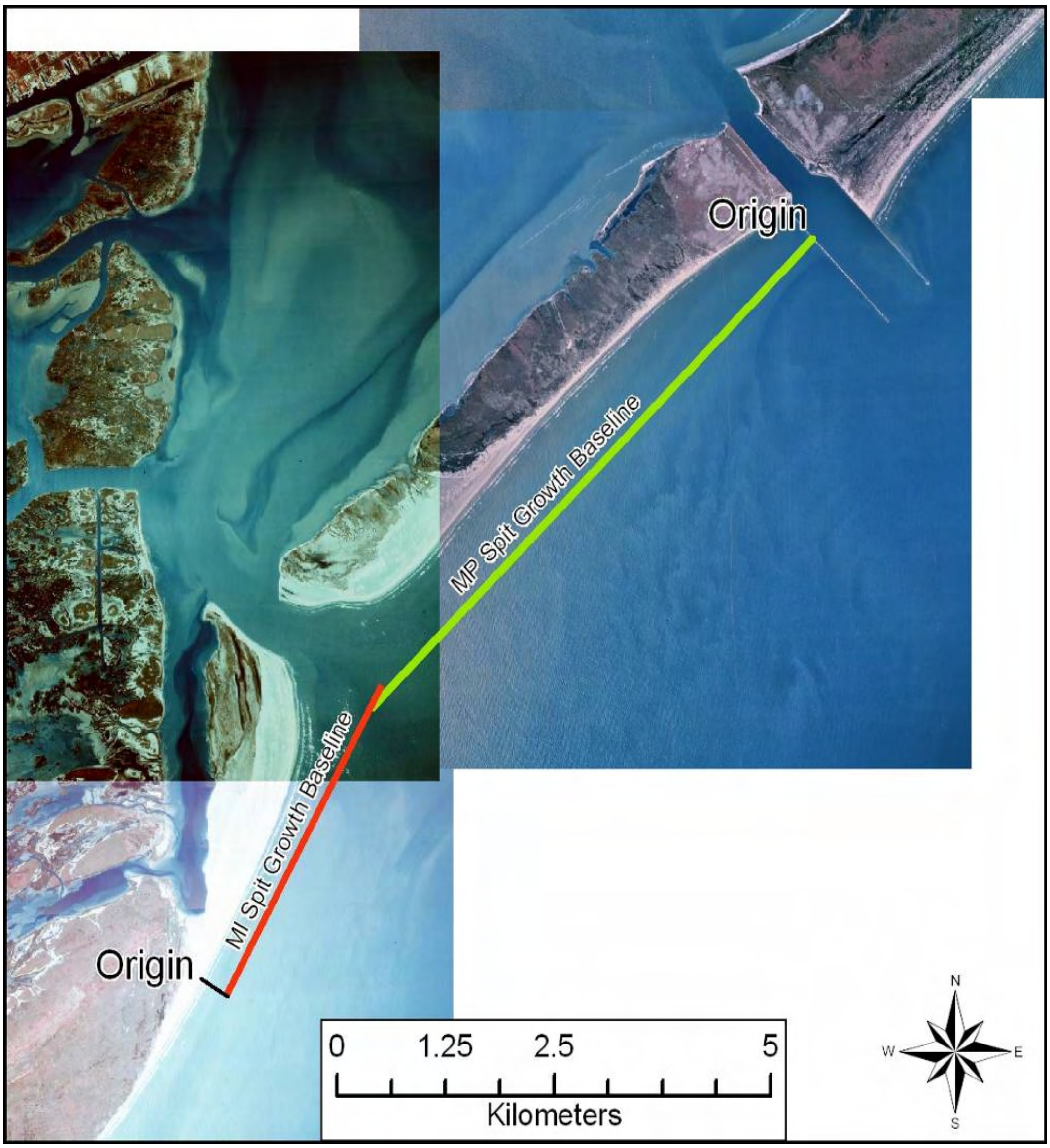


Figure 10. Spit length baselines for Matagorda Island and Matagorda Peninsula.

The width of Pass Cavallo was evaluated in ArcGIS 9.0 from the western-most extent of Matagorda Peninsula shoreline to the easternmost extent of Matagorda Island shoreline. Inlet width was measured by generating a series of parallel lines spaced at 10-m intervals, aligned to the axial orientation of Matagorda Peninsula across the narrowest section of Pass Cavallo. The lines were then intersected with the digitized shoreline, and line length was calculated. The line with the minimum distance was recorded as the inlet width.

## Results

The following sections describe results of the shoreline change and inlet width analyses.

### Shoreline change, Matagorda Peninsula

Shoreline change along Matagorda Peninsula for the extent covered in the 16 May 2006 aerial photographs is plotted in Figure 11. Average updrift rate of shoreline advance was approximately 1.5 m/year. This rate is reduced from the previous interval (1995-2000) of 3 m/year. However, the sampled area is smaller than for the previous interval. Directly updrift of the MSC, the shoreline receded from the position observed in 2000.

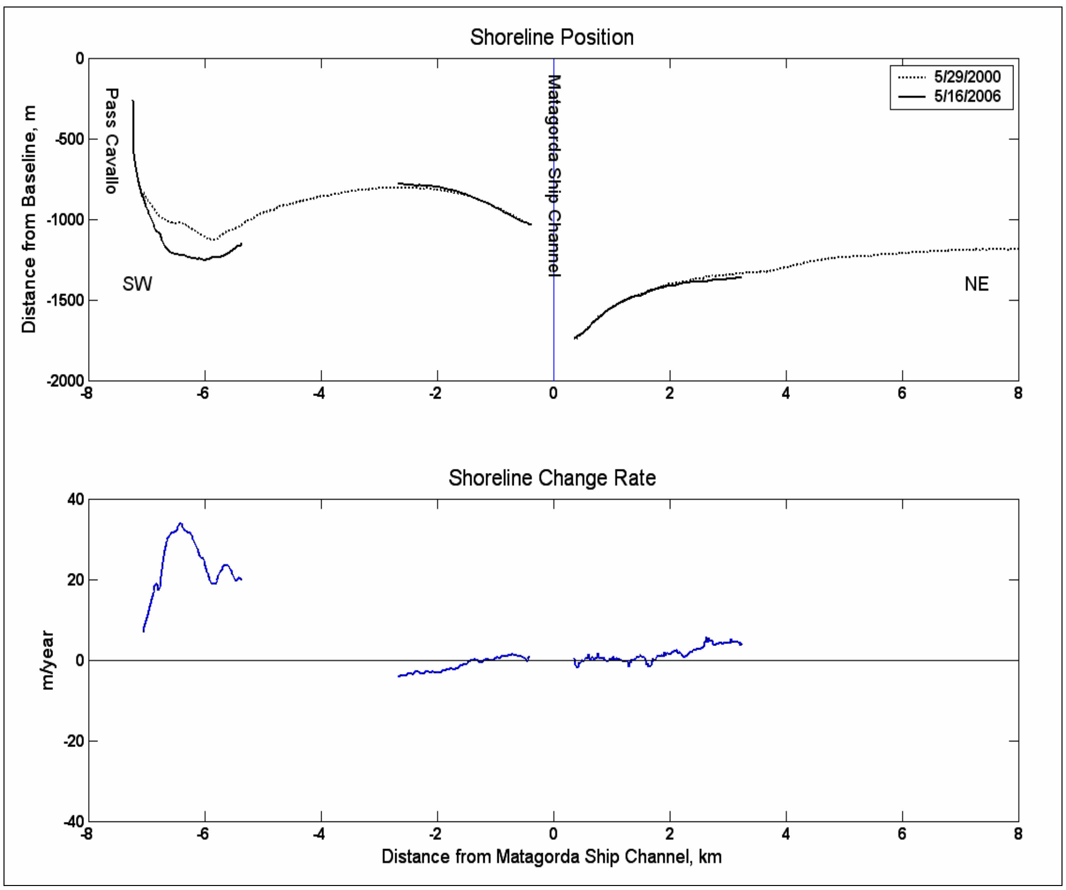


Figure 11. Shoreline position and change, Matagorda Peninsula, May 2000 to May 2006.

Although data were limited downdrift of the MSC, it appears that shoreline recession remains the dominant trend in the area directly downdrift of the MSC entrance. In the area of historic spit growth, shoreline advance is observed at rates between 7.6 and 35.1 m/year, with an average rate of 24.4 m/year for the data coverage. This rate is slightly less than the historical average of 27.1 m/year.

Figure 12 illustrates shoreline change since 2003, as compared to the 1995 shoreline (historical minimum inlet width). The shore directly east of the inlet experienced notable accretion from 2003 to 2006. Between 2006 and 2007, only a small amount of change is observed, although both dates

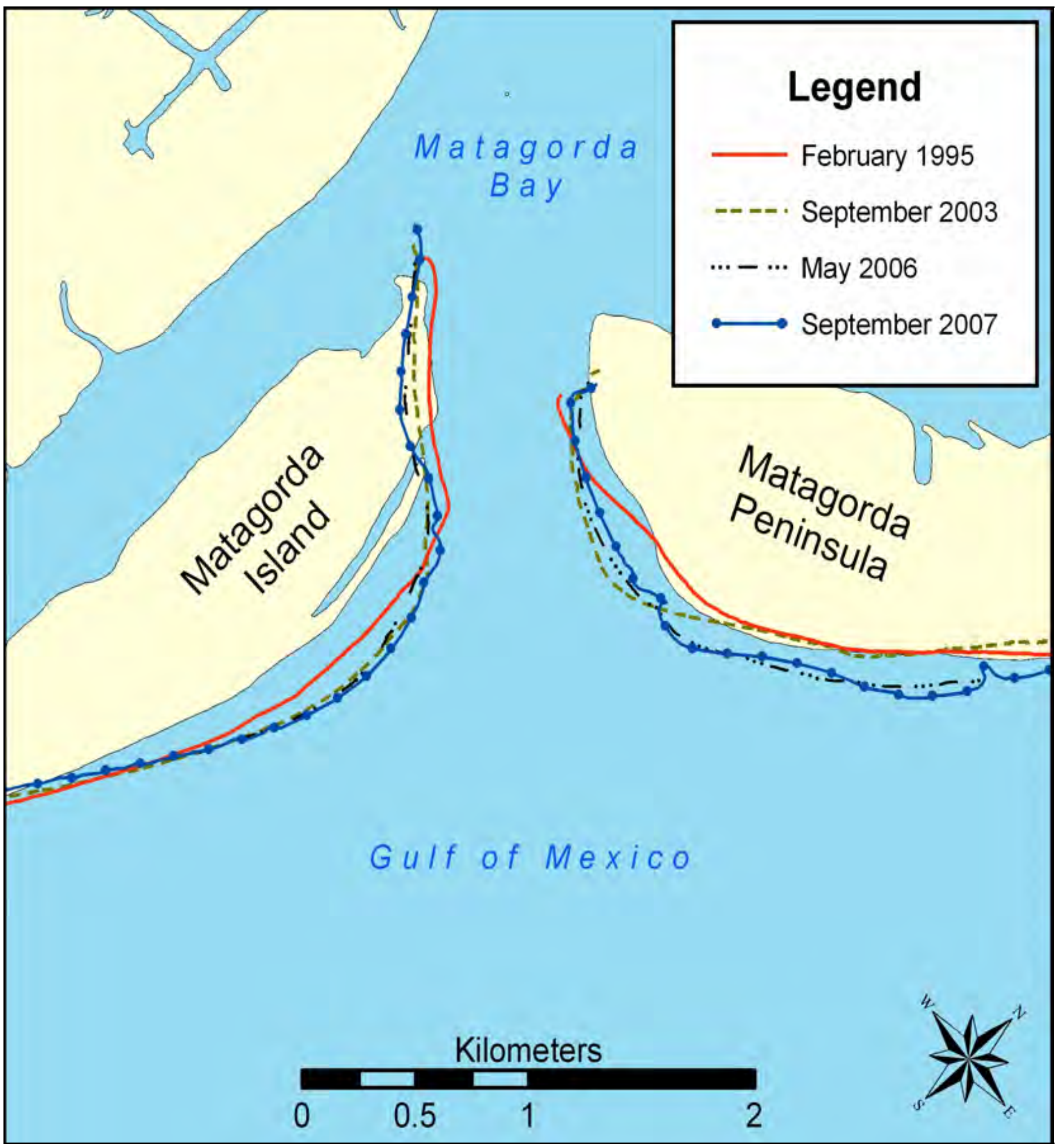


Figure 12. Selected shorelines in near proximity of the inlet, 1995-2007 (background circa 1988-1989).

indicate that the shoreline is successively receding along a south-southwest lobe of the Gulf of Mexico side of the entrance. Matagorda Island exhibits two changes: (a) slight accretion along the south-southeast lobe of the Gulf of Mexico side of the entrance, and (b) successive recession inside the channel from 2003 to 2006 and 2007 (less so from 2006–2007). The present location of the south-southeast lobe of Matagorda Island is similar to the December 1999 position of the shoreline.

### Spit length, Matagorda Peninsula

Changes in the length of Matagorda Peninsula relative to the downdrift (west) jetty at the MSC from 1930 to September 2007 are plotted in Figure 13. Analysis of spit length for Matagorda Peninsula indicates that, since 2003, spit length has increased by 6.1 m. Subsequent to the historic maximum in 1995, spit length decreased by 57.9 m (September 2007). Minimum spit length post-1990 was observed in 2001; the 2007 length is 179.9 m greater. Overall, Era 3 continues to be characterized by small variations of spit length lacking a consistent trend, although it appears that the length of the spit is oscillating around an apparent dynamic equilibrium position.

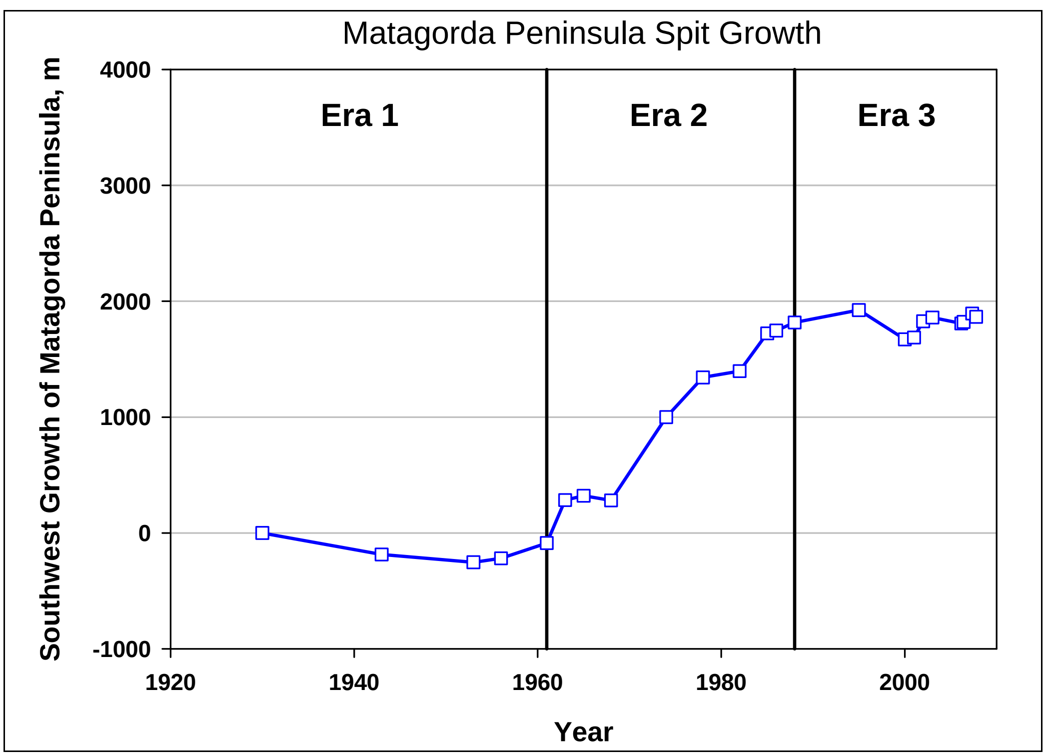


Figure 13. Small variations with no trend of advance or recession characterize Matagorda Peninsula spit length during Era 3.

### Spit length, Matagorda Island

Spit length for Matagorda Island from 1961 to 2007 is plotted in Figure 14. From 2003 to September 2007, little change is observed, and spit length decreased by approximately 30.5 m. The September 2007 spit length is 18.3 m greater than the historical maximum observed in 1986. Although this might be of concern, spit length, as previously defined, is a measure of the maximum length of the Matagorda Island spit. Thus, reported values are more indicative of the position of the northernmost extension of the spit into Matagorda Bay. As shown in Figure 14, recent shoreline changes indicate that the extension of the Matagorda Island spit into the inlet entrance has decreased, while the spit has continued to prograde northward into Matagorda Bay. Northern growth of the spit is responsible for the historical maximum observed in September 2007.

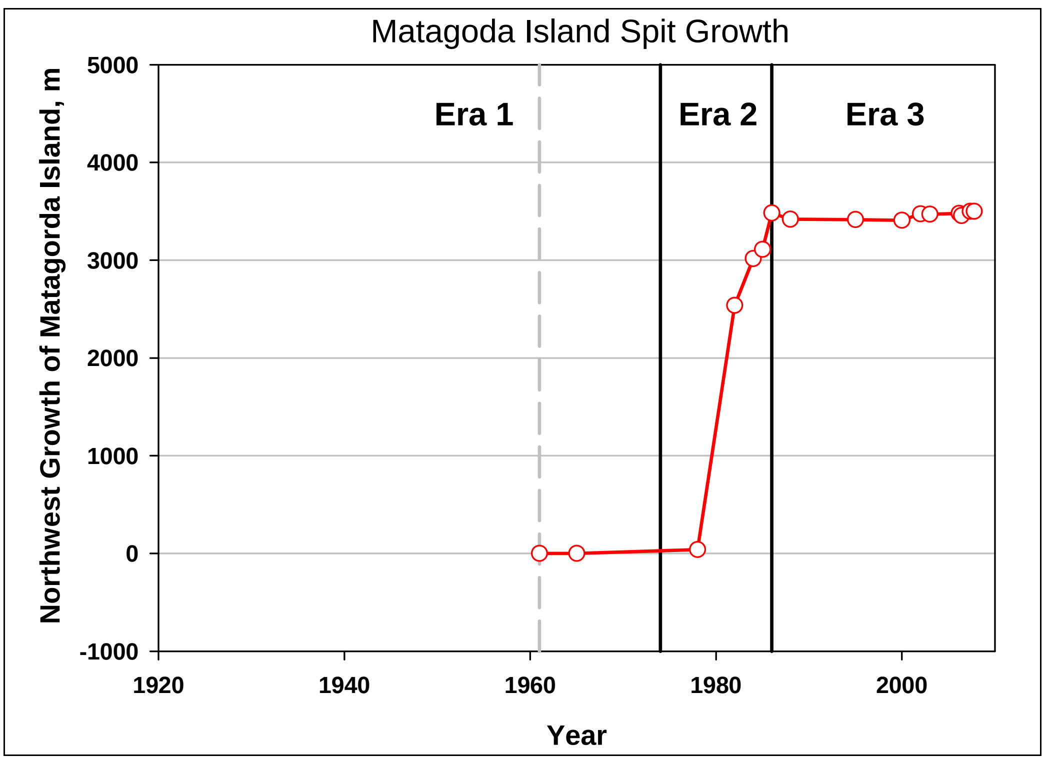


Figure 14. Extent of Matagorda Island spit has been effectively constant since circa 1986.

### Pass Cavallo width

The minimum width of Pass Cavallo serves here as a surrogate for channel cross-sectional area in defining inlet stability. Caution must be exercised in this interpretation, however. Historic change in the width of Pass Cavallo is plotted in Figure 15, and recent change (Era 3, post-1990) is plotted in Figure 16. The inlet widened by approximately 46.0 m between 2003 and 2007. Compared to the historic minimum width in 1995, the inlet is approximately 145.7 m wider in 2007.

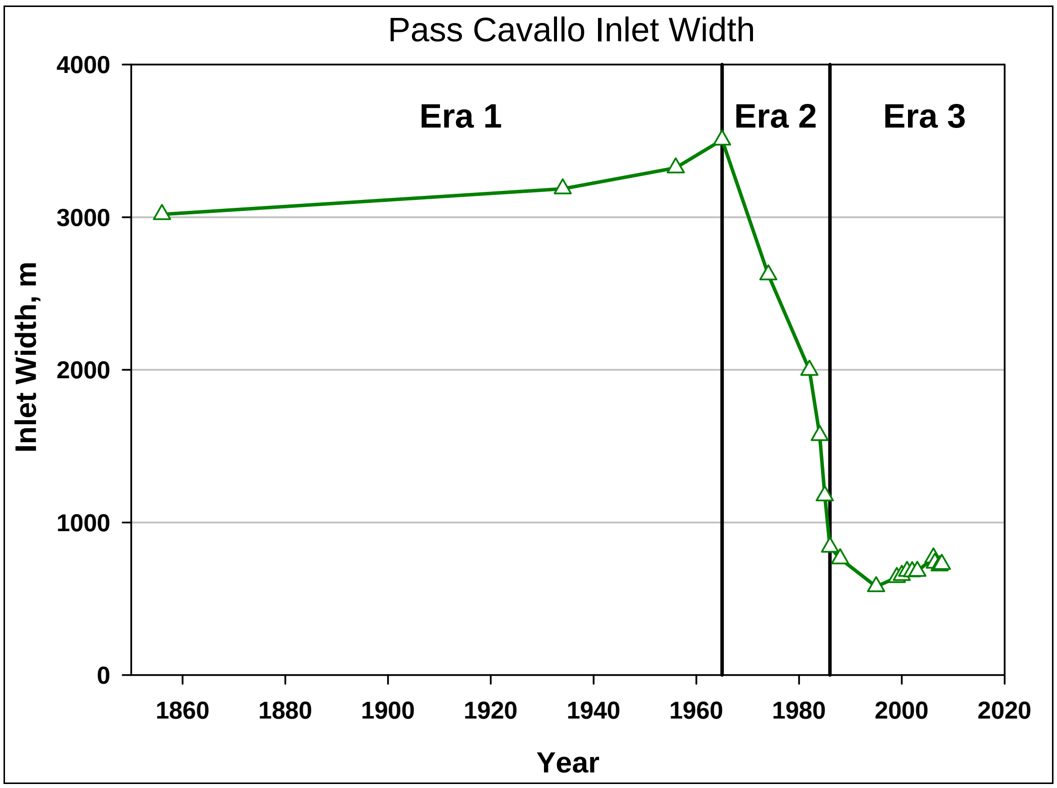


Figure 15. Observed trends in inlet width at Pass Cavallo.

Inlet width obtained by analysis of the most recent aerial photographs (February, May, and December 2006; April and September 2007) appears to have deviated from the trend of continuous widening observed since 1995. To gain insight into the short-term trend in inlet width, successive change and cumulative change subsequent to the historical minimum in 1995 were investigated, and a summary of these metrics is presented in Table 2. Change in inlet width shows variability among the last few aerial surveys; however, these changes appear to coincide with a seasonal cycle.

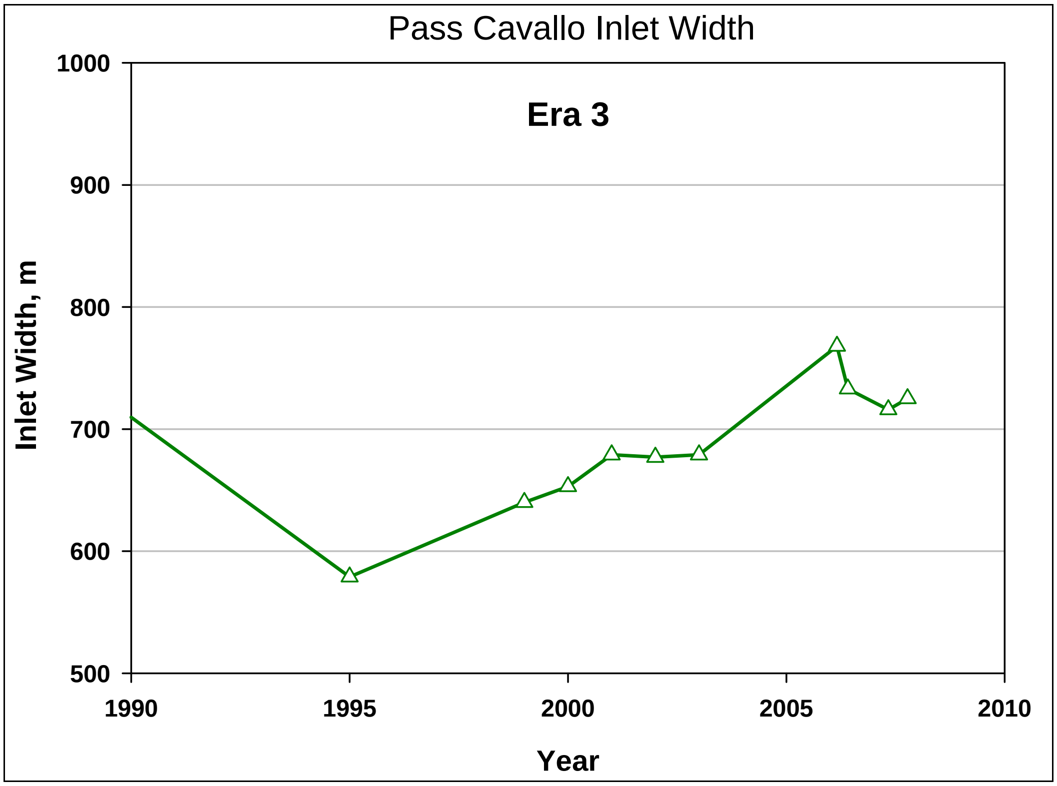


Figure 16. Recent (post-1990) width of Pass Cavallo.

Table 2. Post-1995 change and cumulative change in Inlet width.

| Date | Inlet Width, m | Change in Inlet Width, m | Cumulative Change in Inlet Width, m |
|---|---|---|---|
| February 1995 | 579.3 | 0.0 | 0.0 |
| December 1999 | 639.9 | 60.7 | 60.7 |
| May 2000 | 652.7 | 12.8 | 73.5 |
| January 2001 | 679.0 | 26.2 | 99.7 |
| August 2002 | 676.8 | -2.1 | 97.6 |
| September 2003 | 679.0 | 2.1 | 99.7 |
| February 2006 | 768.3 | 89.3 | 189.0 |
| May 2006 | 714.0 | -54.3 | 134.8 |
| December 2006 | 742.1 | 28.0 | 162.8 |
| April 2007 | 715.9 | -26.2 | 136.6 |
| September 2007 | 725.0 | 9.1 | 145.7 |

Figure 17 plots cumulative inlet width change for all available dates, in addition to dates in the early-to-late summer months. The variability observed in the most recent five aerial dates appears to be related to seasonality, because inlet widths measured for summer months produce seasonal minima, and those measured in winter months, seasonal maxima. This variability was not previously observed because of past limited frequency of image capture of the inlet condition. Data corresponding to summer months (shown as dashed line) indicate a trend of continued increase of inlet width (Figure 17).

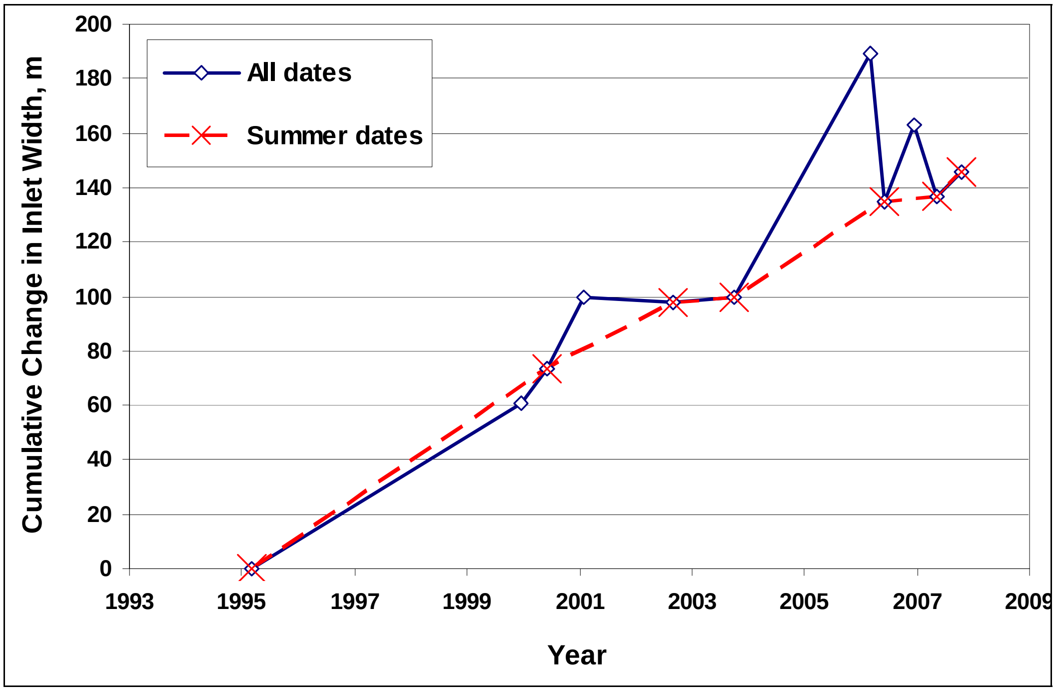


Figure 17. Post-1995 cumulative change and seasonality in inlet width.

## Summary

An updated geomorphic analysis with aerial photographs from 2006 and 2007 demonstrated that Pass Cavallo has remained stable since the previous available observed condition in 2003 (Kraus et al. 2006b). Overall, inlet width increased by approximately 46.0 m. Spit intrusion into Pass Cavallo by Matagorda Island and Peninsula was observed to slightly decrease. Interpretation of the geomorphic data and background information indicates that Pass Cavallo has achieved a new state of dynamic equilibrium caused by reduction of its tidal prism through flow capture by the MSC and by possible depletion of the ebb-tidal shoal that was abandoned in response to the decrease in tidal prism.

# 6 Summary and Conclusions

An 1856 U.S. Coast and Geodetic Survey map of Pass Cavallo shows an entrance width of approximately 2,800 m, with a deep channel (at least 6 m in depth) approximately 305 m wide running along its southern side, adjacent to Matagorda Island. A dynamic ebb-tidal shoal was located between Matagorda Peninsula and this main channel. At that time, Pass Cavallo was one of the largest natural inlets in the Gulf of Mexico. Historically, ephemeral passes such as Greens Bayou and Brown Cedar Cut were opened through Matagorda Peninsula by large storms, but these eventually closed in favor of Pass Cavallo, located in the southwest corner of Matagorda Bay and receiving the benefit of wind tide produced by frequent wind fronts out of the north that occur from October through May. Cutting of the MSC entrance 5.6 km to the north of Pass Cavallo and its stabilization by jetties have caused the volume of water flowing through Pass Cavallo to decrease. Presently, the discharge through the inlet and the associated tidal prism are about one-third of their inferred historic (1856 to 1930) values.

The purpose of the present study was to investigate if Pass Cavallo would remain open or gradually close. Subject to the uncertainties that enter all coastal sediment processes studies, it is concluded that Pass Cavallo will remain open at its present cross-sectional channel area or undergo a moderate increase in channel area, based on the following evidence:

1. Pass Cavallo is located in the southwest corner of Matagorda Bay, and it benefits from the wind tide produced by weather fronts from the north, which adds to the scouring action of the ebb-tidal current.
2. The theoretical cross-sectional channel area corresponding to the present tidal prism at Pass Cavallo, calculated by an empirical equation, is 7,500 $m^2$. In contrast, the measured minimum channel area to msl is presently 2,000–3,500 $m^2$. This result indicates a surplus of sediment that is constricting the channel. Abandonment and collapse of much of the ebb-tidal shoal was identified as the likely source of such sediment. The ebb shoal is being partially abandoned because the tidal prism has been reduced. Eventually, this material will move out of the system, relieving infilling potential for Pass Cavallo and allowing its cross-sectional area to increase. An extensive photographic record indicates that the width of Pass Cavallo has been nearly constant since about 1990. The inlet reached

minimum width of 600 m in 1995 and has been slowly increasing in width since then, up to the last available photograph, taken in September 2007.

3. The channel gorge maximum depth at Pass Cavallo is presently 9 m, a substantial depth consistent with depths found historically (1856–1965). Such a depth would allow the inlet to sustain episodic sediment inputs as might be associated with a hurricane.
4. Widening and deepening of the MSC entrance will not notably change the stability of Pass Cavallo, because the additional capture of the tidal prism by the ship channel will be small relative to the present value of tidal prism for Pass Cavallo and in comparison to past reductions in prism there.

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# Appendix A: Recent Aerial Photography

This appendix contains aerial photographs available to date that are not compiled in Kraus et al. (2006b). Shoreline position and inlet minimum width at Pass Cavallo were analyzed from these photographs.

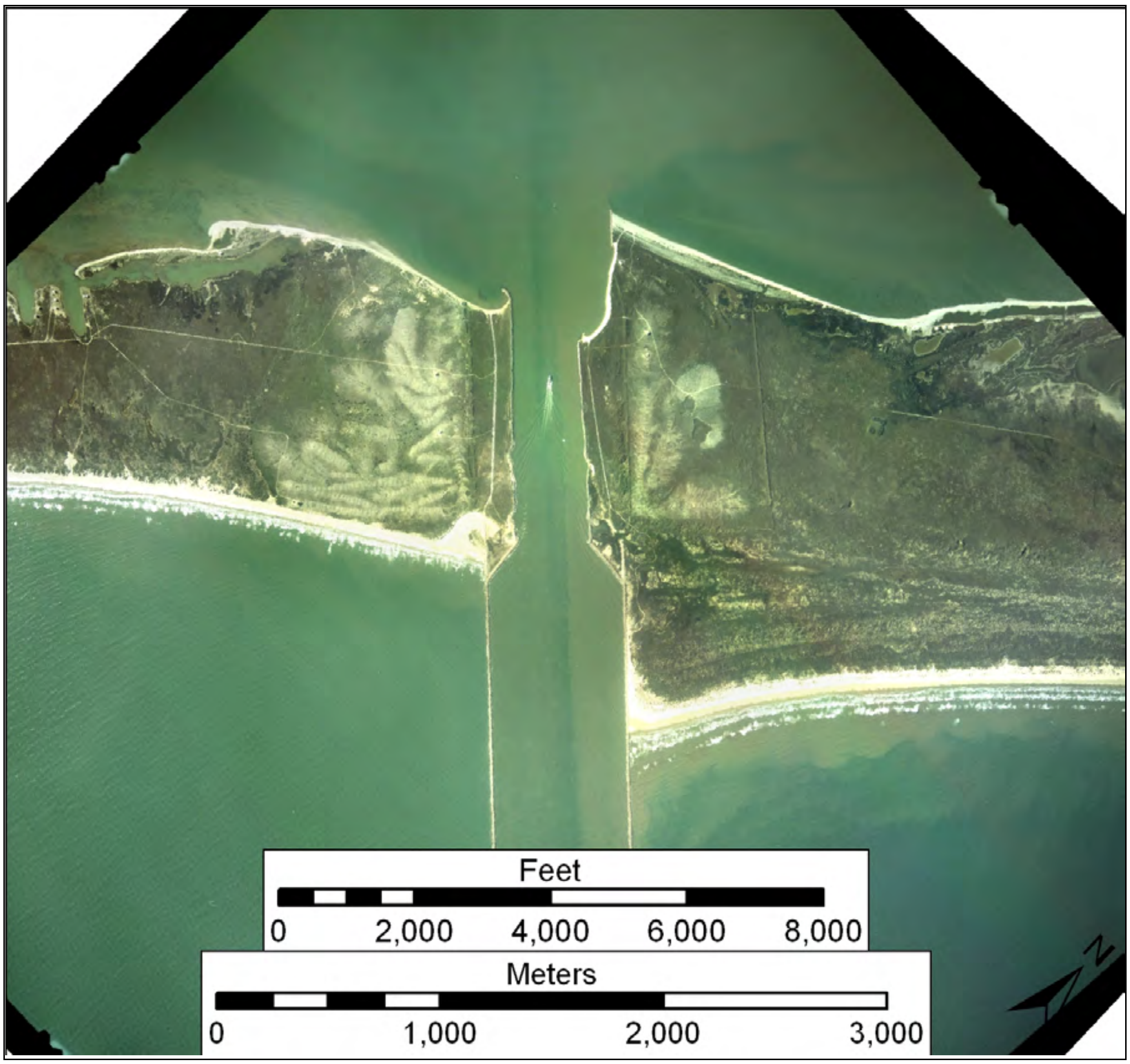


Figure A1. Matagorda Ship Channel, 28 February 2006.

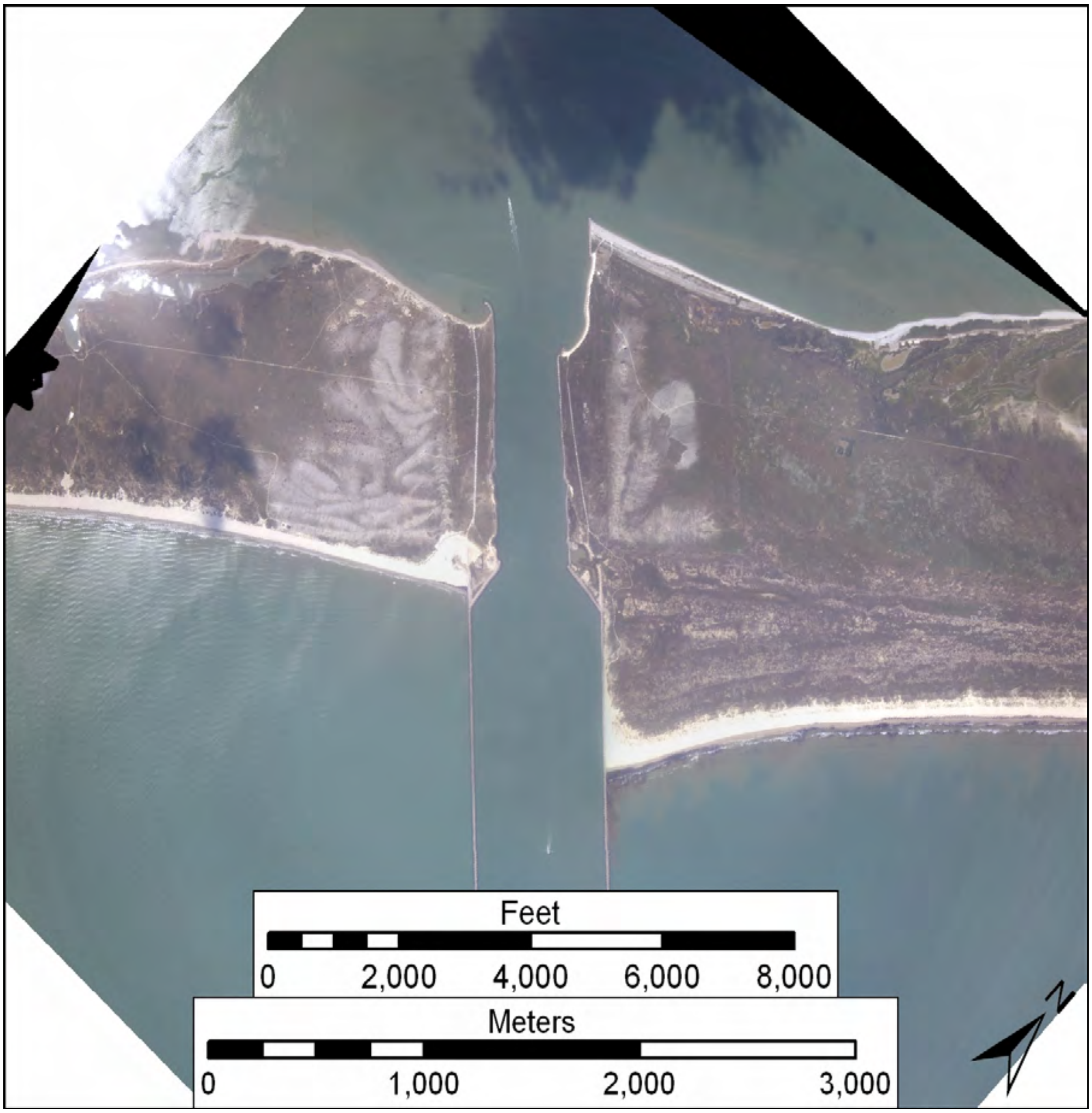


Figure A2. Matagorda Ship Channel, 16 May 2006.

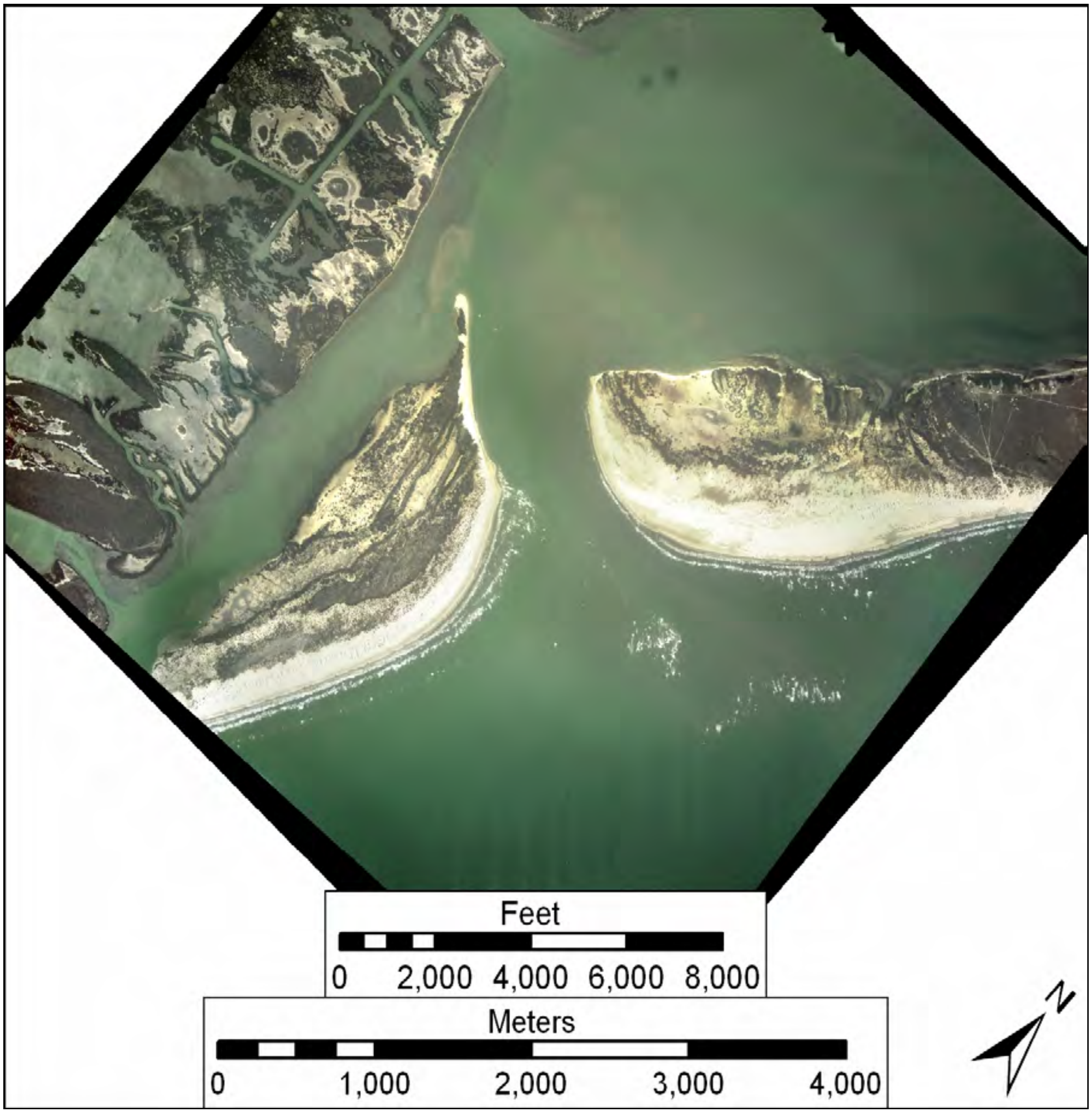


Figure A3. Pass Cavallo, 28 February 2006.

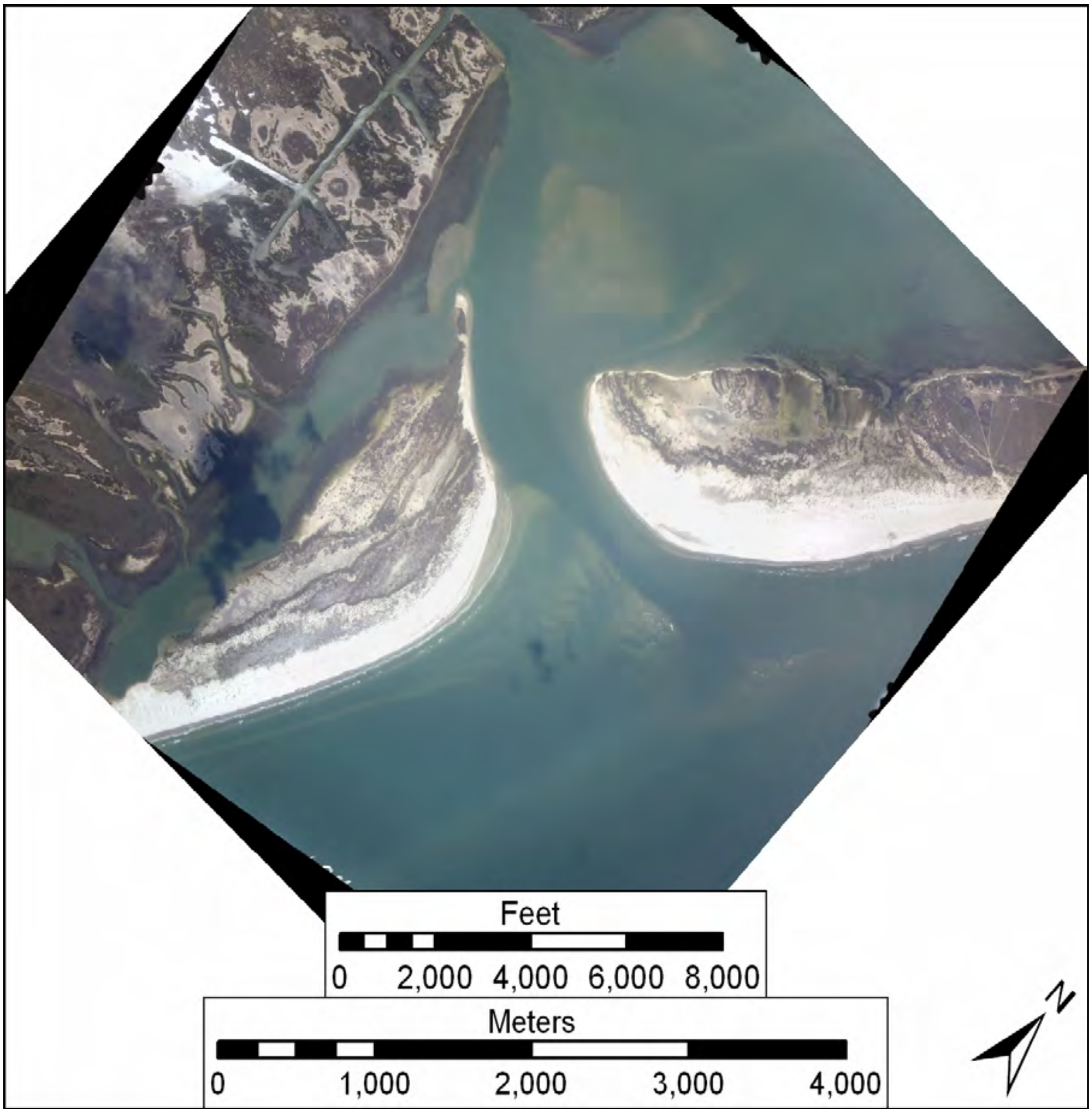


Figure A4. Pass Cavallo, 16 May 2006.

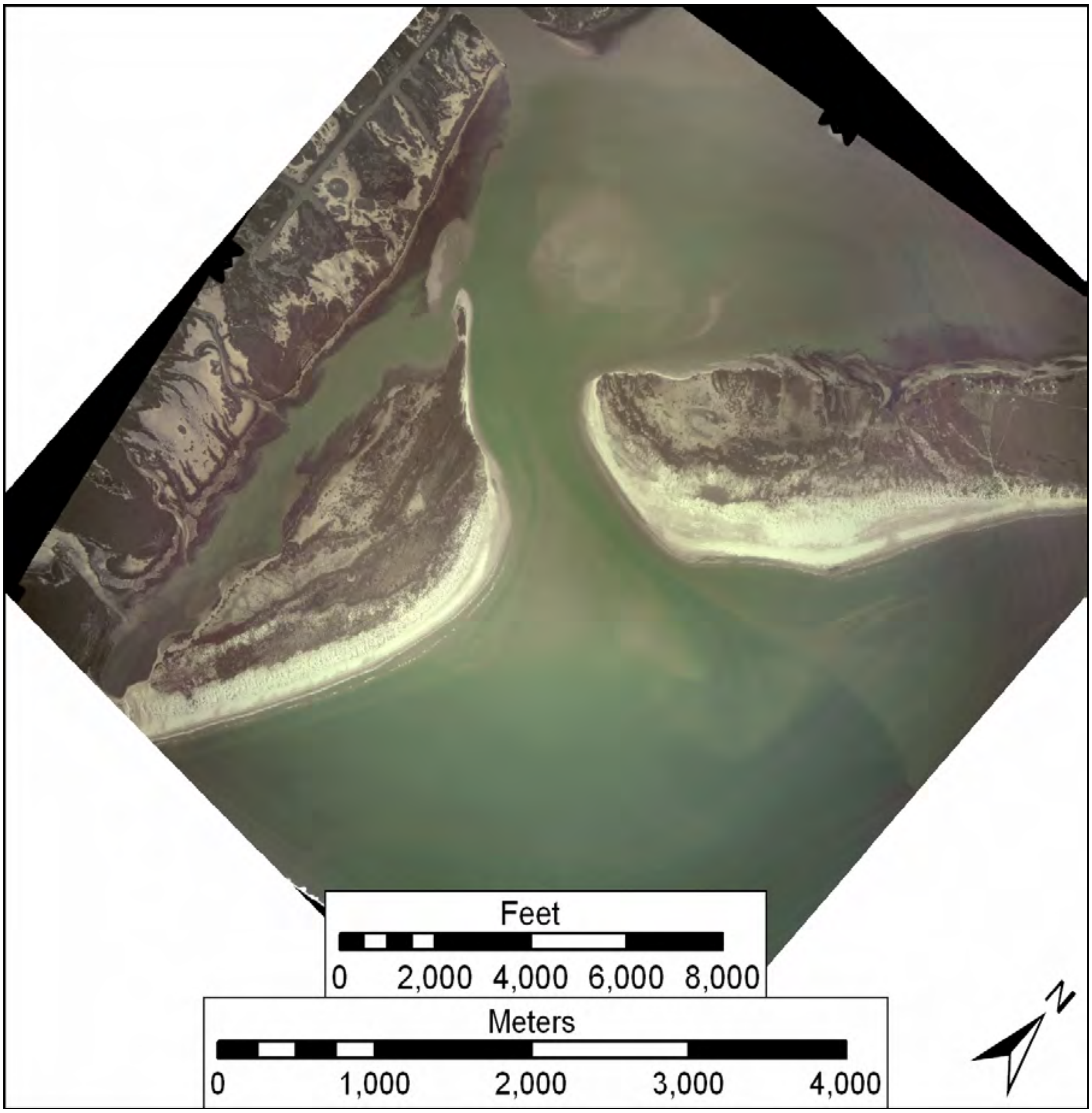


Figure A5. Pass Cavallo, 13 December 2006.

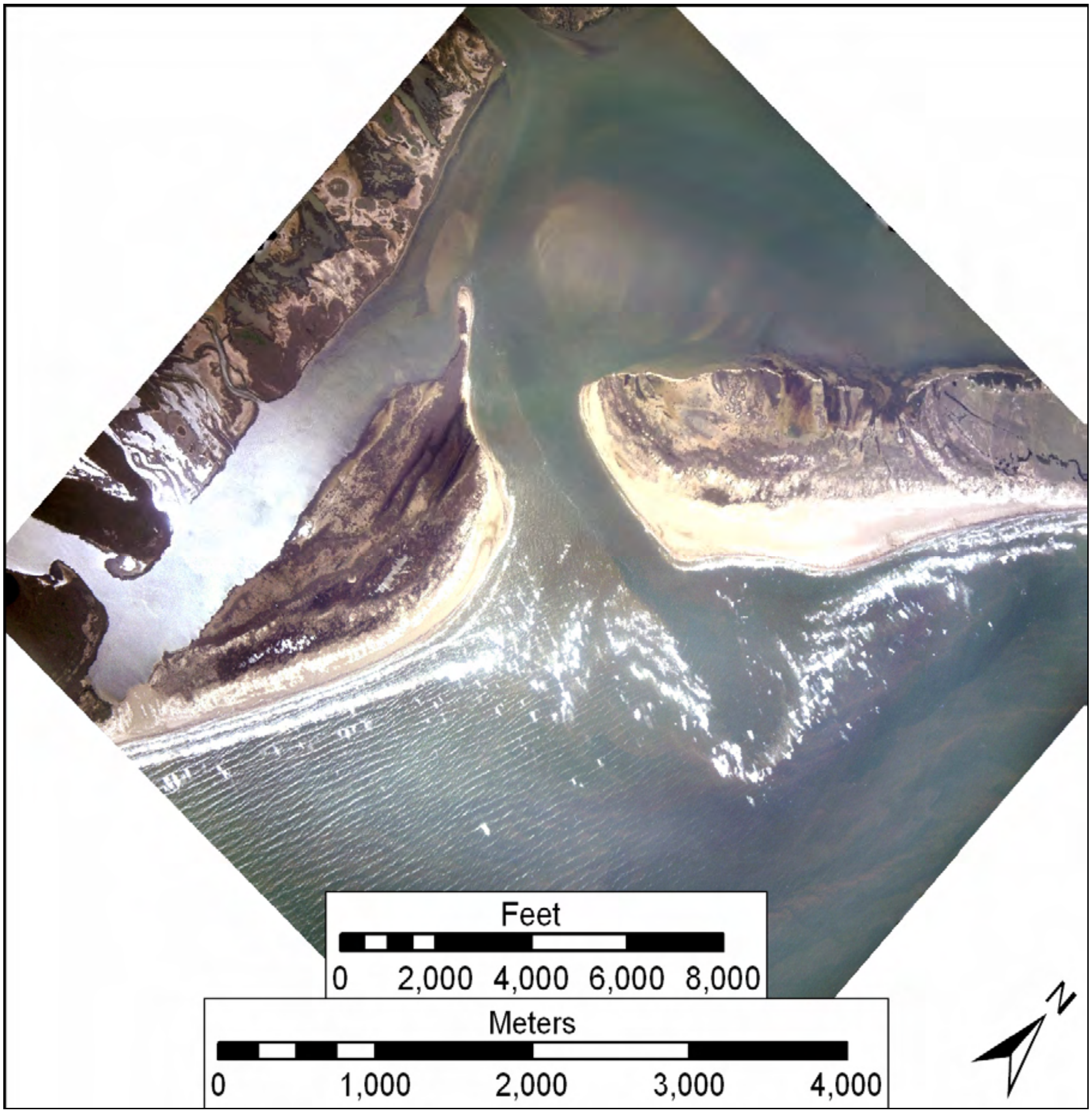


Figure A6. Pass Cavallo, 5 April 2007.

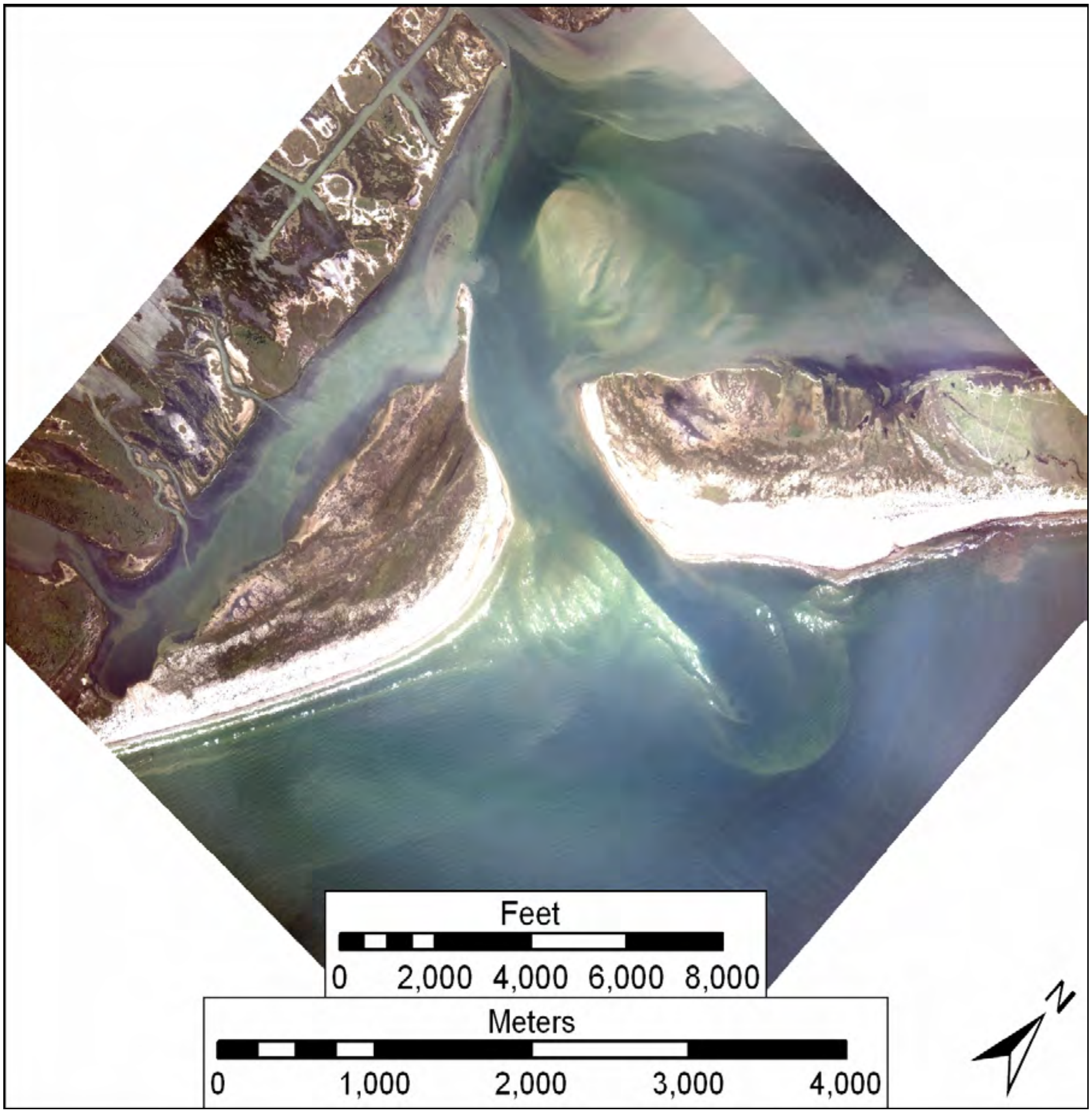


Figure A7. Pass Cavallo, 10 September 2007.

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**14. ABSTRACT**

The study concerns the cross-sectional area stability of Pass Cavallo, a natural coastal inlet located in the southwest corner of Matagorda Bay, Texas. The width of Pass Cavallo has decreased since opening of the Matagorda Ship Channel (MSC) entrance to Matagorda Bay in 1966. The process of narrowing began after separation of Matagorda Bay into East Matagorda Bay and the present Matagorda Bay by formation of the Colorado River delta during 1929–1935. The deep-draft MSC enters the bay 3.5 miles (5.6 km) to the north of Pass Cavallo and is a more efficient tidal channel by joining with a deeper and more central portion of the bay.

Tidal inlets are maintained in a dynamic equilibrium through a balance of coastal and inlet processes. Conceptually, longshore transport of sediment by waves and the wave-induced current tends to fill an inlet, whereas the ebb-tide and flood-tide currents through the inlet scour its channel. The most reliable approach for examining inlet stability, and that taken here, is based upon accepted empirical predictive relations, supported by measurements made at Pass Cavallo. Collapse of a portion of the ebb-tidal shoal at Pass Cavallo after construction of the MSC entrance is posited as being responsible for much of the reduction in cross-sectional channel area of Pass Cavallo. Since the mid-1990s, the width of Pass Cavallo has been stable, suggesting the sediment load to the inlet from collapse of its ebb shoal has declined. Subject to the uncertainties that enter all coastal sediment processes studies, it is concluded that Pass Cavallo will remain open at its present dynamic cross-sectional channel area or undergo a moderate increase in channel area.

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| | | |
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